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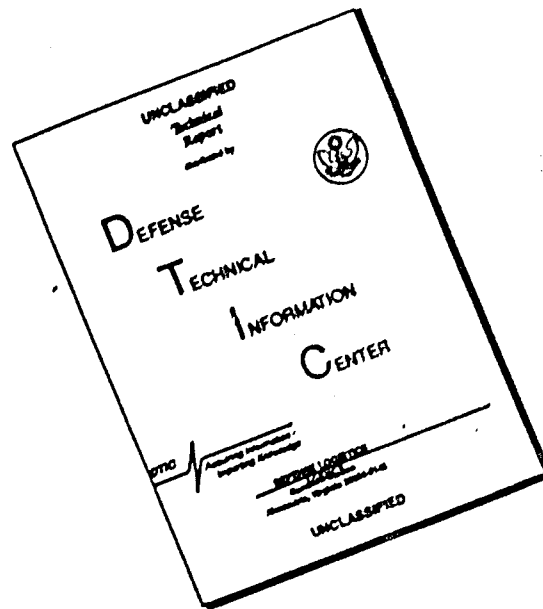
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TRANSPORTATION RESEARCH COMMAND  
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TRECOM TECHNICAL REPORT 63-58

PERFORMANCE AND OPERATION OF QUASI  
TWO-DIMENSIONAL JET FLAPS

Task 1D121401A14224  
(Formerly Task 9R38-11-009-24)  
Grant DA TC-44-177-G1

November 1963

prepared by:

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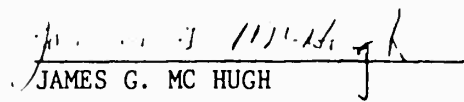
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FORT EUSTIS, VIRGINIA

This report has been reviewed by the U. S. Army Transportation Research Command and is considered to be technically sound. The report is published for the exchange of information and stimulation of ideas.

  
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Task 1D121401A14224  
(Formerly Task 9R38-11-009-24)  
Grant DA TC-44-177-G1  
TRECOM Technical Report 63-58  
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UTIA Report 90

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# LIST OF SYMBOLS

$J$	jet momentum ( $= M \cdot V_J$ )
$a_0$	a constant (see equation 2. 2a)
$c_\mu$	jet momentum coefficient ( $= J/q \cdot S_W$ )
$M$	mass flow
$V_0$	free-stream velocity
$V_J$	jet-flow velocity
$S_W$	wing area
$C_I$	a constant (see equation 2. 2b)
$C_D$	drag coefficient of wing without blowing
$C_{DT}$	total drag coefficient of jet-flapped wing
$C_L$	lift coefficient of wing without blowing
$C_{LT}$	total-lift coefficient of jet-flapped wing
$C_{LJ}$	jet-induced pressure lift
$\theta$	jet-deflection angle
$\alpha$	angle of attack
$C_{TM}$	total measured thrust as measured with a balance
$C_{TP_i}$	ideal jet-induced pressure thrust
$C_{DP}$	profile drag coefficient for wing without blowing
$C_{DJ}$	jet drag ( $= \Delta C_{DP}$ )
$C_{TR}$	jet-reaction thrust ( $= c_\mu \cdot \cos \tau$ )
$C_{DJ_0}$	jet drag at zero jet-deflection angle
$a(\theta)$	drag parameter, depending on $\theta$
$a(\alpha)$	drag parameter, depending on $\alpha$

$C'_{Di}$	induced drag coefficient for wing without blowing
AR	aspect ratio
$a(0)$	a constant (see equation 3.4)
$C_2$	a constant (see equation 3.3)
$C_{Di}$	induced drag coefficient of jet-flapped wing
$C_{LR}$	jet reaction lift coefficient ( $= c_{\mu} \cdot \sin \tau$ )
K	a constant (see equation 2.6)
$K'$	a constant (see equation 2.23)
$K''$	a constant (see equation 2.11)
$\Delta C_{TM}$	change in total thrust coefficient due to blowing  ( $\Delta C_{TM} = C_{TM} + C'_{D} = c_{\mu} - \Delta C_{DT}$ )
$\Delta C_{DT}$	change in total drag coefficient due to blowing  ( $\Delta C_{DT} = c_{\mu} - C_{TM} - C'_{D}$ )
$a_0$	a constant
$\Delta C_{LT}$	change in total lift coefficient due to blowing  ( $\Delta C_{LT} = C_{LT} - C'_{L}$ )
$\Delta C_{DP}$	change in profile drag coefficient due to blowing ( $= C_{DJ}$ )
<u>Subscripts</u>	
c	calculated
min	minimum

## SUMMARY

In Part I of this report, truly two-dimensional and quasi two-dimensional jet-flap test results are evaluated for experimental evidence in favor or against the once much-disputed jet-flap thrust hypothesis. The thrust hypothesis is verified experimentally as conclusively as it has been proven theoretically.

Part II presents the development of a jet-flap "characteristics" for truly and quasi two-dimensional jet-flapped wings. For any desired lift, it renders any number of combinations of rate of blowing, jet-deflection angle, and angle of attack which can produce this lift. Besides, it permits that amount of the jet-sheet thrust which can be recovered as propulsive thrust or which is nullified by the drag of the jet-flapped wing to be read off simultaneously. The ratio of these values reflects on the performance and economy of operation of this wing. If then, the production of a specific lift is optimized with respect to the lowest expenditure in blowing at the smallest possible drag, an "operating line" can be defined and added to the jet-flap "characteristics". The range of economical jet-flap operation was found to coincide with the region in which any change in the rate of blowing results in exactly the same change in the measured thrust. It is further demonstrated that this portion of a "characteristics" can be constructed or supplemented by the use of the semi-empirical relationships presented, if three "constants" peculiar to the jet-flapped wing in question are known from test results.

## 1. INTRODUCTION

The once much-disputed jet-flap thrust hypothesis has long since been verified theoretically. Experimentally, however, because of the inherent complexity of experimentally separating thrust and drag, it was as late as 1959 that Foley and Reid (reference 1) announced "the significant finding that substantially complete thrust recovery has been obtained in two-dimensional flow tests of a jet flap wing". This claim of only "substantially complete thrust recovery" is due to an apparent recovery of only 94% of the jet-momentum thrust instead of the 100% which the much older English (reference 2 and 3) and French (reference 4) two-dimensional jet-flap test results, if plotted in Foley's and Reid's fashion, suggest. It will be shown subsequently that a thrust recovery less than 100% is illogical and that Foley's and Reid's test results, if used correctly, also demonstrate complete thrust recovery.

In the scrutiny of existing jet-flap test results, one finds that not enough attention has been paid to the application of these results to actual flight vehicles. Consequently, required data is often lacking. This is especially true for information such as how the performance of jet-flapped wings changes as a function of jet-deflection angle, angle of attack, rate of blowing, jet-flap configuration, aspect ratio, etc. To a similar or even greater extent, it applies to data on the economy of jet-flap operation such as the expenditure of blowing to achieve a specific lift and the resulting drag penalty. Further, it applies to questions of how the jet-flap potential as a high-lift device can be best applied to aircrafts. Both performance and economy of operation are, of course, vital parameters for the design of an STOL-jet-flap aircraft. Finally, the whole concept of complete integration of the propulsive system of an aircraft with its lifting system needs critical examination as to its practical promises. This evaluation again strongly hinges on knowing the performance and economy of operation of specifically three-dimensional jet-flapped wings.

The basic requirement of all the above problem areas is to find a way of presenting jet-flap test results (i. e. the lift, drag, jet-deflection angle, angle of attack, slot-blowing rates and engine thrust, efficiency of lift production, economic operation ranges, etc.) in one chart, that is, in a kind of jet-flap "characteristics". This is the aim of the work described in this report.

## II. THE THRUST HYPOTHESIS

### 2.1 PRESENTATION OF THE PROBLEMS

If the full-span jet sheet of a jet-flapped wing in flight is expelled from its trailing edge slot under any angle with the wing chord, a jet reaction lift,  $C_{LR}$ , (see figure 1) and a jet-induced pressure lift,  $C_{LJ}$ , are added to the conventional lift of the wing (lift with no blowing).

In thrust direction one would expect only the action of the jet reaction thrust,  $C_{TR}$ , (see figure 1). However, the thrust hypothesis maintains that, for two-dimensional jet-flapped wings in ideal fluid flow, the total thrust is equal to the full momentum of the jet sheet independent of its angle of deflection,  $\theta$ .

Theoretically, the thrust hypothesis was verified by several researchers (reference 5). Experimentally, because of the complex, composite nature of the drag of jet-flapped wings, neither the National Gas Turbine Establishment, Pyestock (N.G.T.E.) nor Office National D'Etudes Et De Recherches Aeronautiques (O.N.E.R.A.) succeeded in verifying it unambiguously. It was not before 1959 that Foley and Reid (reference 1) experimentally proved the thrust hypothesis to be true. By a novel way of plotting their own but still conventional test results, they succeeded in presenting the "thrust recovery" as the slope of the seemingly straight  $C_{LT} = \text{constant}$  lines (figure 2). Note that this slope infers a thrust recovery of 94% only; this fact induced Foley and Reid to conclude that, instead of the mandatory 100%-thrust recovery, only "substantially complete and uniform thrust recovery was attained under all of the operating conditions which prevailed during these tests".

This statement requires clarification. Besides it was felt that Foley's and Reid's novel way of plotting jet-flap test results should open new avenues in unravelling the synthesis of the total drag of jet-flapped wings at zero and non-zero angles of attack.

### 2.2 Experimental Verification

As has been mentioned already, theory confirms the thrust hypothesis (reference 6, 7 and 8) for two-dimensional jet-flapped wings in ideal fluid flow. Experimental results of quasi two-dimensional jet-flapped wings at zero angle of attack, as originally presented by N.G.T.E. (reference 2 and 3) and O.N.E.R.A. (reference 4) did not prove this, but they did suggest the thrust hypothesis to be true. For instance, with the jet sheet being deflected vertically down ( $\theta = 90^\circ$ ) (see reference 2), one would have expected to measure a drag, if one questions the validity of the thrust hypothesis. The N.G.T.E., however, actually measured a thrust of almost 40% of  $c_{\mu}$ . No doubt this thrust has to be part of the

induced pressure thrust,  $C_{TP_i}$  (see figure 1), which theory for the  $\theta = 90^\circ$  case predicts to be equal to  $c_\mu$ . The missing or undetectable 60% of  $c_\mu$  is counteracted and eliminated by various component drags which are part of the total drag.

Credit is to be given to Foley and Reid (reference 1) who analysed their conventional jet-flap test results in such a way as to present the variations in measured thrust with  $c_\mu$  at constant values of the total lift,  $C_{LT}$ , (see figure 2). The thrust recovery thus appears as the slope of the  $C_{LT}$  - constant lines. For any  $C_{LT}$  = constant line all components of the total drag which are functions of  $C_{LT}$ , for example, the induced drag,  $C_{D_i}$ , or the profile drag,  $C_{DP}$ , do not change. Therefore, they cannot obscure the changes in thrust (or the thrust recovery) if  $c_\mu$  and  $\theta$  are varied.

It should be mentioned here that in all so-called two-dimensional tests of jet-flapped wings,  $C_{D_i}$  actually is not zero. This is because the aspect ratio of jet-flapped wings in experimental investigations is never truly infinite. In so-called two-dimensional tests, aspect ratios were actually found to be as low as 6.8.

## 2.3 Complete (100%) Thrust Recovery

### 2.3.1 Experimental Evidence

Assume that the individual lines of constant total lift are straight over the entire operating range of a jet-flapped wing (see figure 2 and 3). These lines indicate 100% thrust recovery if, increasing  $c_\mu$  at constant total lift, the measured thrust increases by exactly the same amount as  $c_\mu$  increases, or if

$$d(\Delta C_{TM})/d c_\mu = 1$$

Since, according to theory,

$$\Delta C_{TM} = c_\mu - \Delta C_{DT},$$

it follows that  $d(\Delta C_{DT})/d c_\mu = 0$  or that

$$\Delta C_{DT} = \text{constant} = f(\Delta C_{LT}).$$

In other words, the total drag of a jet-flapped wing does not change if  $c_\mu$  and  $\theta$  are changed in such a way as to keep the total lift constant.

If one plots the test data obtained for various two-dimensional jet-flapped wings (reference 2, 3 and 4) in Foley's and Reid's way, they all (see reference 9) except Foley's and Reid's own data (see figure 3 or 4 of

reference 1), suggest a 100% thrust recovery.

### 2.3.2 The Total Drag as a Function of $c_{\mu}$ and $\theta$

In the University of Toronto, Institute of Aerophysics (UTIA) Report No. 64, it was shown (see also figures 4 and 5 of this report) that

$$\Delta C_{DT} = a(\theta) c_{\mu} \quad (2.1)$$

where  $a(\theta)$  was found to be

$$a(\theta) = a_0 + a_1(\theta) \quad (2.2a)$$

which (see figure 6) for  $\theta > 0$  can be approximated by

$$a(\theta) = C_1 \sin^2 \theta \quad (2.2b)$$

where  $C_1$  is the slope of the straight line by which the actual  $a(\theta)$  versus  $\sin^2 \theta$  curve can be approximated. If, however, the jet-deflection angle  $\theta$  approaches zero,  $a(\theta)$  approaches  $a_0$  and not, as equation (2.2b) suggests zero. This fact should be kept in mind whenever equation (2.1) is used.

If equation (2.2a) is substituted into equation (2.1) the result is

$$\Delta C_{DT} = a_1(\theta) c_{\mu} + a_0 c_{\mu} \quad (2.3)$$

which, at all practical jet-deflection angles ( $\theta > 0$ ), can be reduced to

$$\Delta C_{DT} = a(\theta) c_{\mu} = C_1 \sin^2 \theta c_{\mu} . \quad (2.4)$$

In the case of  $\theta = 0$ , a symmetrical jet-flapped wing at zero angle of attack produces no lift and its total drag reduces to the profile drag

$$\Delta C_{DP} = a_0 c_{\mu} = C_{DJ_0} , \quad (2.5)$$

which (see section 2.6.2), according to definition, is known as jet drag. More specifically, it is the jet drag,  $C_{DJ_0}$ , at zero jet-deflection angle.

If, as concluded in the previous section, 2.3.1,  $\Delta C_{DT}$  is constant for the case of 100% thrust recovery, equation (2.4) predicts that the effects on  $\Delta C_{DT}$  of changes in  $c_{\mu}$  and  $\theta$  must eliminate each other, provided that the total lift is kept constant. Further, lines of constant  $\Delta C_{DT}$  in figure 4, for example, simultaneously represent lines of constant  $\Delta C_{LT}$  and, at intersections with the total drag curves, define pairs of  $\theta$  and  $c_{\mu}$  values which keep the total lift fixed.

Since, along a  $\Delta C_{LT} = \text{constant}$  line, the induced drag,  $C_{Di}$ , is also constant (if one assumes  $\pi AR \gg 2c_\mu$ ), it follows that the profile drag does not change along the straight portion of the  $\Delta C_{LT} = \text{constant}$  line. When, however, a  $\Delta C_{LT} = \text{constant}$  line starts to deviate from a straight line, an increase in total drag results from the fact that the profile drag with increasing jet-deflection angle rises faster than the profile drag due to reduced blowing (called jet drag, see section 2.6.2) falls off.

### 2.3.3 The Total Drag as a Function of $\Delta C_{LT}$

If equation (2.4) is combined with the theoretical expression

$$\Delta C_{LT}^2 = K^2 \sin^2 \theta c_\mu, \quad (2.6)$$

(derived by Spence in reference 10) another expression for the total drag, provided that  $\theta > 0$ , results as

$$\Delta C_{DT} = \frac{C_1}{K^2} \Delta C_{LT}^2 \quad (2.7)$$

where  $K$  is given by Spence as

$$K = 2 \pi^{\frac{1}{2}} + 0.325 c_\mu^{\frac{1}{2}} + 0.156 c_\mu \quad (2.8)$$

and plotted in figure 7.  $K$  can be represented in a somewhat simpler form as

$$K = 3.65 + 0.35 c_\mu. \quad (2.9)$$

Assuming an average  $\bar{K} = 4$  over the range  $0 < c_\mu \leq 2$ , we see that the maximum possible deviation of  $\bar{K}$  from the  $K$  of equation (2.9) is less than  $\pm 10\%$ .

Equation (2.7) permits us, if  $C_1$  and  $K$  are known, to calculate the  $\Delta C_{DT}$  as a function of  $\Delta C_{LT}^2$ . If  $C_1$  and  $K$  were constants over the entire or part of the operating range of the jet-flapped wing considered, equation (2.7) says that over this range

$$d(\Delta C_{DT})/d\Delta C_{LT}^2 = \text{constant} \quad (2.10)$$

In principle this relationship is known to apply to conventional wings and in analogy suggests that the total drag of a jet-flapped wing may be written therefore as

$$\Delta C_{DT} = \text{Profile Drag} + \text{Induced Drag}$$

or

$$\Delta C_{DT} = K'' \Delta C_{LT}^2 + C_{Di}. \quad (2.11)$$

The induced drag,  $C_{Di}$ , according to Maskell and Spence (reference 11) is given by

$$C_{Di} = \frac{\Delta C_{LT}^2}{\pi AR + 2 c_{\mu}} = \frac{\Delta C_{LT}^2}{\pi AR (1 + \frac{2 c_{\mu}}{\pi AR})} \quad (2.12)$$

For symmetrical aerofoil profiles, customary with jet-flapped wings,  $\Delta C_{LT} = C_{LT}$ , since  $C'_L = 0$ , if  $c_{\mu} = 0$  (no blowing and  $\alpha = 0$ ).

Combining equation (2.7) and (2.11) we get

$$\Delta C_{DT} = \frac{C_1}{K^2} \Delta C_{LT}^2 = K'' \Delta C_{LT}^2 + \frac{\Delta C_{LT}^2}{\pi AR (1 + \frac{2 c_{\mu}}{\pi AR})} \quad (2.13)$$

= constant,

provided that  $\theta > 0$  and  $\Delta C_{LT}$  is kept constant.

From this equation for quasi two-dimensional wings it follows, assuming  $c_{\mu}$  to be small in comparison with the aspect ratio and therefore  $C_{Di}$  to be constant, that  $K''$  must be constant, as it is for conventional wings. Since the change in profile drag of jet-flapped wings caused by changes in  $c_{\mu}$  is known as the jet drag, it follows that in case of a 100% thrust recovery, the so-called jet drag must be counterbalanced by an equal but opposite change in profile drag due to changes in  $\theta$  so that actually no net change in profile drag takes place. The constant  $K''$  can be obtained from equation (2.13)

$$K'' = \frac{C_1}{K^2} - \frac{1}{\pi AR + 2 c_{\mu}} \quad (2.14)$$

which for very high aspect ratio wings (truly two-dimensional wings) becomes

$$K'' = \frac{C_1}{K^2} \quad (2.15)$$

#### 2.3.4 Experimental Check of the $d(\Delta C_{DT})/d(\Delta C_{LT}^2) = \text{Constant}$ Relationship

If we draw a horizontal line in either figure 3 or figure 10 so that it cuts all  $\Delta C_{LT} = \text{constant}$  lines where they are straight (see line A-A), we can read off  $\Delta C_{DT} = c_{\mu} - \Delta C_{TM}$ . If we plot the obtained  $\Delta C_{DT}$  values versus  $\Delta C_{LT}^2$  for the pure jet-flapped wing, the wing with symmetrical blowing (both of reference 4) and the wing of reference 1 with

upper surface blowing, figure 8 is obtained. This figure obviously demonstrates that jet-flapped wings at various configurations satisfy the equation

$$d(\Delta C_{DT}) / d(\Delta C_{LT}^2) = \text{constant} \quad (2.10)$$

as long as the thrust recovery is 100%.

Finally, figure 9, a plot of  $\Delta C_{DT}$  versus  $\Delta C_{LT}^2$  with  $\theta$  as the parameter, is added to demonstrate the collapsing effect (see figure 8) which a proper reduction of parameters, here, by keeping the lift constant, may have.

#### 2.4 Incomplete Thrust Recovery

Figures 2 and 3 seem to suggest that the  $C_{LT} = \text{constant}$  lines are straight over the entire operating range of jet-flapped wings. That this is not so is shown in section 2.5.

Whereas the slopes of the  $\Delta C_{LT}$  lines of figure 3 do indicate 100% thrust recovery, the slopes of the  $C_{LT} = \text{constant}$  lines of figure 2 demonstrate a thrust recovery of 94% only. Foley and Reid acknowledge this finding by stating that they have found "substantially complete and uniform thrust recovery", not complete (100%)-thrust recovery.

Since all other available two-dimensional jet-flap test results (reference 2, 3 and 4) seem to indicate a 100%-thrust recovery (see figure 3 and also figure 2 of reference 5), the question of why the test results of reference 1 show a thrust recovery of only 94% for the straight portion of the lines of  $C_{LT} = \text{constant}$  arises.

It is obvious that Foley's and Reid's 94%-thrust recovery is due to the fact that their measured values are plotted versus a "calculated"  $c_{\mu c}$  instead of versus the actual jet coefficient, which according to reference 1 is smaller by 6 to 9% than the calculated  $c_{\mu c}$ . If Foley's and Reid's test data are plotted versus the actual  $c_{\mu}$ , taken as  $c_{\mu} = 0.94 \cdot c_{\mu c}$ , their results also demonstrate the mandatory 100% thrust recovery. This is clearly demonstrated by looking at their figure 4 (figure 4 of reference 1), where, after the  $c_{\mu}$  correction, the experimental line of "slope - 0.94" would coincide with the complete recovery "slope - 1.0" line.

Theoretically, for two-dimensional jet-flapped wings in ideal fluid flow, the total thrust is equal to the full momentum of the jet sheet independent of its angle of deflection,  $\theta$ . Foley and Reid, by plotting their conventional experimental results for fixed values of the total lift, also found the way for proving experimentally complete (100%) thrust recovery by

showing that the thrust increases or decreases by the same amount by which  $c_{\mu}$  is increased or decreased. This is illustrated in figure 10, which was obtained from Foley's and Reid's test results after replott-ing them as  $\Delta$  -values (changes due to blowing) versus the actual jet coefficients. The slopes of the straight portion of the  $\Delta C_{LT} = \text{constant}$  lines indicate the mandatory 100% thrust recovery. Those portions of the  $\Delta C_{LT} = \text{constant}$  lines which deviate from a straight line demonstrate that along them, the thrust  $\Delta C_{TM}$  is decreasing faster than  $c_{\mu}$  de-creases. This case and other experiments which apparently do not prove complete thrust recovery (see also section 2.5) do neither invalidate the thrust hypothesis nor the fact that in these cases the thrust is also actually completely recovered. They only show that the missing or undetectable portion of the thrust force is counterbalanced by an equal but opposite drag force. Mathematically, the changes in thrust and drag due to an increase in blowing,  $\delta c_{\mu}$ , follow from

$$c_{\mu} + \delta c_{\mu} - (\Delta C_{TM} + \delta \Delta C_{TM}) = \Delta C_{DT} + \delta \Delta C_{DT}. \quad (2.16)$$

Since

$$c_{\mu} - \Delta C_{TM} = \Delta C_{DT}$$

and since  $\delta \Delta C_{DT} = 0$  for 100% thrust recovery, we get

$$\delta \Delta C_{TM} = \delta c_{\mu}. \quad (2.17)$$

For apparently incomplete thrust recovery, the above equation becomes

$$\delta \Delta C_{TM} = \delta c_{\mu} - \delta \Delta C_{DT}. \quad (2.18)$$

This means that the measured thrust increase,  $\delta \Delta C_{TM}$ , is smaller than  $\delta c_{\mu}$  (the real increase in thrust) by the amount  $\delta \Delta C_{DT}$ , the simultaneous increase in total drag induced when  $c_{\mu}$  is increased by  $\delta c_{\mu}$ .

Note that the term "incomplete thrust recovery" is misleading and is used actually to describe experimental evidence with obeys equation (2.18).

## 2.5 Thrust Recovery and Operating Range

If one plots the test data of reference 1 and 4 over the whole operat-ing range, figures 10, 11, and 12 are obtained. They all show that at large  $c_{\mu}$  values and  $\theta > 50$ , the lines of  $C_{LT} = \text{constant}$  become curved. They further show that at small  $c_{\mu}$  values, the smaller  $C_{LT}$  the smaller the jet-deflection angle,  $\theta$ , becomes at which a 100% thrust recovery can still be secured.

The deviation of the  $\Delta C_{LT} = \text{constant}$  lines from a straight line is obviously due to the fact that  $\Delta C_{DT}$  is increasing instead of remaining constant, or that along a  $\Delta C_{LT} = \text{constant}$  line

$$\Delta C_{DT} = \frac{C_1}{K^2} \Delta C_{LT}^2 + \text{constant} \quad (2.19)$$

In other words  $C_1$  and  $K$  can now no longer be constants.

### 2.5.1 The Variation in K

From Spence's equation (reference 10)

$$\Delta C_{LT}^2 = K^2 \sin^2 \theta c_\mu \quad (2.6)$$

we can obtain the variation of  $K$  from figure 10, 11, and 12 if we read off the values of  $c_\mu$  and  $\theta$  along each  $\Delta C_{LT} = \text{constant}$  line. For O. N. E. R. A.'s pure jet-flapped wing,  $K$  is compared in figure 7 with Spence's theoretical value. In figure 13, the  $K$  values for an upper-surface, blown flap and a jet-flapped wing with symmetrical blowing are shown and compared with figure 7.

Figure 13 demonstrates that the more  $K$  deviates from a constant value, the smaller  $c_\mu$  and  $\Delta C_{LT}$  are and the larger the jet deflection angle is. It is this deviation of  $K$  which also clearly shows up in figure 10, 11, and 12 and which is primarily responsible for the strong curvature of the  $\Delta C_{LT}$  lines, especially at small lift values.

Note that  $K$ , in all three cases presented, can be considered a constant for lift coefficients which are higher than those which conventional or flapped aerofoils could supply anyway. Note also that  $K$  is a value characteristic of the chosen jet-flapped wing configuration. Jet-flapped wings with jet-control flaps, which at equal  $c_\mu$  and  $\theta$  can produce higher lift coefficients than pure jet flaps, have higher  $K$  values. Besides,  $K$  must also depend on aspect ratio.

### 2.5.2 The Variation of $C_1$

We find  $C_1$  from equation (2.2b) as

$$C_1 = a(\theta) / \sin^2 \theta \quad (2.20)$$

where  $a(\theta)$  is obtained from

$$\Delta C_{DT} = a(\theta) c_\mu \quad (2.1)$$

as the slope of the  $\Delta C_{DT}$  versus  $c_\mu$  lines. Figures 4, 5, and 14 show

such plottings. Note that these lines are practically straight and should go through the origin.

If the slopes of these lines are then plotted against  $\sin^2\theta$ , figure 15 is obtained. It shows that as long as  $\theta$  is smaller than approximately 55 degrees,  $C_1$  can be considered as constant for at least two of the three jet-flapped wings presented. The obvious vagueness of the  $a(\theta)$  values for the wing of reference 1 is believed to stem from the inaccuracy of the initial data which had to be extracted from small scale graphs (see figure 2 of reference 1).

If in figure 15, the  $a(\theta)$  values of the N. G. T. E. jet-flapped wing (reference 2 and 3) are added, figure 6 results which represents the  $a(\theta)$  values from all quasi two-dimensional jet-flap test results available up-to-date. Figure 6 suggests an average value of  $\bar{C}_1 = 0.63$  for all quasi two-dimensional jet-flapped wings.

## 2.6 The Ideal Jet-Flapped Wing in Operation

Equation (2.4) stated that for  $0 < \theta < 50^\circ$

$$\Delta C_{DT} = C_1 \sin^2\theta c_\mu = \text{constant}$$

as long as the  $\Delta C_{LT} = \text{constant}$  lines are straight. In other words, lines of  $\Delta C_{DT} = \text{constant}$  are horizontal lines in Figs. 4, 5, and 14, and each of these lines corresponds to a specific lift value,  $\Delta C_{LT}$ , which can be obtained from

$$\Delta C_{LT} = \frac{K}{\sqrt{C_1}} (\Delta C_{DT})^{\frac{1}{2}} \quad (2.21)$$

In figure 16, the test data of figure 11 and 14 for the pure jet-flap of reference 4 are combined. The straight portions of the  $\Delta C_{LT} = \text{constant}$  lines indicate complete (100%) thrust recovery. The curved portions designate that part of the operational range of the jet-flapped aerofoil, where the large jet-deflection angles employed demand stronger blowing (higher  $c_\mu$  values) in order to compensate for and overcome an increasing, instead of constant, profile drag.

Figure 16 represents the "characteristics" for the pure jet-flapped wing of reference 4 at zero angle of attack.

### 2.6.1 Most Economical Operation at Zero Angle of Attack

By nature, the jet flap is a high-lift device. Its lift is primarily a function of angle of attack, jet deflection angle, and rate of blowing.

A specific lift is produced most economically if both  $c_{\mu}$  and  $\Delta C_{DT}$  are the smallest values possible.

If one operates to the right of point A (see figure 16) along the  $\Delta C_{LT} = 3$  line, operation is uneconomical because the lift is primarily due to blowing (high  $c_{\mu}$ ) and the potential of the jet-deflection angle as a means for producing lift is not fully utilized. Any lift due to  $\theta$  is free of charge, as long as the thrust recovery is complete, and leads to a potential reduction of the amount of blowing required to produce it.

Operation, however, to the left of point A along the  $\Delta C_{LT} = 3$  line indicates that e. g. at  $\theta = 71^{\circ}$ , the actually required jet coefficient,  $c_{\mu a} = 0.67$ . If the thrust recovery would, however, still be 100%, the ideal jet coefficient required would be  $c_{\mu i} = 0.49$  (see figure 16).

Note that at low  $\Delta C_{LT}$  values the range of  $\theta$  values providing complete thrust recovery is rather small (for  $\Delta C_{LT} = 1$ ,  $0 < \theta < 33^{\circ}$ ). However, for such small lift coefficients ( $\Delta C_{LT} < 1.5$ ), one would not employ jet-flapped wings anyway. Note too (see also figure 12) that at high  $\Delta C_{LT}$  values,  $\theta$  does not seem to exceed  $60^{\circ}$ , if complete thrust recovery is to be secured.

For most economical lift production, jet-flapped wings should be operated along the "operating line" which is obtained by connecting the points at which the  $\Delta C_{LT} = \text{constant}$  lines start to deviate from a straight line. These points designate the lowest possible  $c_{\mu}$  and total drag values at which a specific lift can be produced. Such an operating line is shown in both the upper and lower plot of figure 16. Note that this operating line is about parallel with the  $\theta = 63^{\circ}$  line. This indicates that jet-deflection angles of  $\theta > 60^{\circ}$  should not be exceeded if this jet-flapped wing is to be operated most economically.

In practice, operating a jet-flapped wing at the lowest possible  $c_{\mu}$  and  $\Delta C_{DT}$  for attaining a required lift may satisfy the lift requirements most economically, but does not necessarily simultaneously provide the required propulsive thrust for the aircraft. If the rate of blowing required for thrust exceeds that for most economical lift production, the jet-flapped wing will operate at a point on the respective  $\Delta C_{LT} = \text{constant}$  line but below the operating line. Theoretically, this wing is still as efficient as before, since the increase in  $c_{\mu}$  is completely recovered as thrust, in spite of the fact that the jet deflection angle  $\theta$  has to be reduced to satisfy the equation

$$\sin \theta = \frac{\Delta C_{LT}}{\bar{K} \cdot c_{\mu}^{\frac{1}{2}}}$$

If, however, the  $c_{\mu}$  required for thrust is much larger than that required for lift, one should, for practical reasons, consider to duct to and expell through the wing trailing edge slots only that portion of the total jet-engine exhaust which is needed for lift production. This scheme would reduce duct losses, structural weight, and duct occupied wing space.

## 2.6.2 The Jet Drag, $C_{DJ}$

The jet drag is defined as the change in profile drag due to blowing. Experimentally,  $C_{DJ}$  is difficult to single out and to determine except in the case of a symmetrical jet-flapped wing at zero angle of attack and zero jet-deflection angle (or zero lift). In this latter case

$$C_{DJ_0} = \Delta C_{DP} = c_{\mu} - \Delta C_{TM}, \quad (2.22)$$

and test data of reference 2 (or see figure 77 of reference 5) show that the jet drag of zero jet-deflection angle obeys the following relationships

$$\begin{aligned} C_{DJ_0} &= K' c_{\mu} = 0.06 c_{\mu} \text{ for } c_{\mu} < 0.1 \\ C_{DJ_0} &= 0.01 \text{ to } 0.017 c_{\mu} \text{ for } c_{\mu} > 0.1 \end{aligned} \quad (2.23)$$

where the magnitude of  $K'$  seems to depend on the chordal Reynolds number. According to equation (2.5),  $K' = a_0$ .

Physically, the jet drag is composed of pressure and friction drag acting in close proximity with the wing's trailing edge, plus mixing drag due to mixing of the jet sheet, particularly in its strongly curved region, with the surrounding air.

In the above case, when  $\alpha = 0$  and  $\theta = 0$ , the jet drag is a function of  $c_{\mu}$  only. If  $\theta$  is not zero but is a constant, the jet drag could be obtained as follows. We know that  $\theta > 0$

$$\Delta C_{DT} = C_1 \sin^2 \theta c_{\mu} \quad (2.5)$$

and that

$$\Delta C_{DT} = \Delta C_{DP} + C_{Di}$$

Therefore

$$\Delta C_{DP} = C_1 \sin^2 \theta c_{\mu} - C_{Di}, \quad (2.24)$$

which for  $\theta = \text{constant}$  becomes

$$\Delta C_{DP} = C_{DJ} = a(\theta) c_{\mu} - C_{Di}. \quad (2.25)$$

There,  $C_{Di}$  is not a constant because  $\Delta C_{LT}$  is not constant if  $c_\mu$  is changed while  $\theta$  is kept constant (see, for example, figure 16 or equation (2.6)). The induced drag can, however, be calculated from

$$C_{Di} = \frac{\Delta C_{LT}^2}{\pi AR + 2 c_\mu} \quad (2.12)$$

if  $AR$  is known. Substituting

$$\Delta C_{LT}^2 = \bar{K}^2 \sin^2 \theta c_\mu \quad (2.6)$$

in the equation for  $C_{Di}$ , equation (2.25) becomes for  $0 < \theta = \text{constant}$ .

$$\begin{aligned} C_{DJ} &= a(\theta) c_\mu \left[ 1 - \frac{\bar{K}^2}{C_1(\pi AR + 2 c_\mu)} \right] \\ &= C_1 \sin^2 \theta c_\mu \left[ 1 - \frac{\bar{K}^2}{C_1(\pi AR + 2 c_\mu)} \right] \end{aligned} \quad (2.26)$$

or  $C_{DJ}/\Delta C_{DT} = \text{constant}$ , if  $AR \gg 2 c_\mu$ .

Equation (2.26) is plotted in figure 17a and b. In figure 17a,  $C_{DJ}$  is compared with  $\Delta C_{DT}$  and  $C_{Di}$  for the  $\theta = 55^\circ$  jet-deflection angle. In figure 17b, the jet drag is shown as a function of  $\theta$ , demonstrating the well-known fact that  $C_{DJ}$  increases rapidly with jet-deflection angle. Equation (2.26) further illustrates that  $C_{DJ}$  decreases for large  $\bar{K}$  values (which are a trademark of jet-control flaps with surface blowing). The nominal constant  $C_1$  has little effect on  $C_{DJ}$  since it does not change much (see figure 15) from wing to wing configuration. Note also that high aspect ratio aerofoils cause larger jet drags.

Next, we have to consider the jet drag of a jet-flapped wing which is operating along the straight portion (100% thrust recovery) of a  $\Delta C_{LT} = \text{constant}$  line. We know that in this case the total drag does not change, and  $C_{Di}$  is a constant if we neglect the small changes caused by  $c_\mu$  (assume  $\pi AR \gg 2 c_\mu$ ). It follows then from

$$\Delta C_{DT} = \Delta C_{DP} + C_{Di}$$

that

$$\Delta C_{DP} = \text{constant}$$

This means that all changes in profile drag  $\delta C_{DP}$  due to changes in  $c_\mu$  must be counterbalanced by opposite changes in profile drag  $\delta C_{DP}$  due to changes in  $\theta$  such that no net change in  $\Delta C_{DP}$  takes place, or

$$\delta(\Delta C_{DP}) = \delta C_{DJ} - \delta C_{DP} = 0,$$

or

$$\delta C_{DJ} = \delta C_{DP} \text{ (see figure 17b).} \quad (2.27)$$

In this case, equation (2.24) becomes

$$\Delta C_{DP} = C_1 \sin^2 \theta c_{\mu} \left[ 1 - \frac{\bar{K}^2}{C_1(\pi AR + 2 c_{\mu})} \right]. \quad (2.28)$$

If in figure 11, for example, the jet-deflection angle  $\theta$  is changed from  $33^\circ$  to  $55^\circ$  at constant  $\Delta C_{LT} = 2$ , we could think of going from point A to point B either directly along the  $\Delta C_{LT} = 2$  line or via the paths ACB or ADB.

Let us analyse the path ACB. A change along AC means that no change in jet drag takes place due to  $c_{\mu} = \text{constant}$ . The total drag, however, changes by an amount  $\delta \Delta C_{DT} = 0.175$  (see figure 11) that can also be calculated from

$$\delta \Delta C_{DT} = C_1 c_{\mu} [\sin^2 55^\circ - \sin^2 33^\circ] = 0.178.$$

The change in profile drag follows then from equation (2.27) and (2.26) for  $R = 4.1$  and  $C_1 = 0.55$  as

$$\begin{aligned} \delta C_{DP} &= \delta \Delta C_{DT} \left[ 1 - \frac{\bar{K}^2}{C_1(\pi AR + 2 c_{\mu})} \right] \\ &= 0.178 \cdot 0.525 = 0.0935. \end{aligned}$$

The change in jet drag along path CB can be read from figure 17b as

$$\delta C_{DJ} = 0.095,$$

or it can be calculated from equation (2.26)

$$\begin{aligned} \delta C_{DJ} &= C_1 \sin^2 55^\circ \left[ c_{\mu_C} \cdot 0.525 - c_{\mu_B} \cdot 0.52 \right] \\ &= 0.55 \cdot 0.672 \left[ 0.86 \cdot 0.525 - 0.39 \cdot 0.52 \right] \end{aligned}$$

as

$$\delta C_{DJ} = 0.095.$$

This proves that equation (2.27) is in agreement with actual experimental results.

### III. THE JET-FLAPPED WING AT AN ANGLE OF ATTACK

Unfortunately, there is only one set of quasi two-dimensional test results available (O.N.E.R.A., reference 4) which presents the drag of a pure jet-flapped wing as a function of the wing's angle of attack. The jet deflection angle in these tests is kept constant at  $\theta = 55^\circ$ .

Another set exists (reference 4) but it is for  $\theta = 90^\circ$  and at the low aspect ratio of  $AR = 3$ .

#### 3.1 EVALUATION OF THE TEST DATA

The test results of figure 9, of reference 4, replotted in Foley's and Reid's fashion, are shown in figure 18a, b, and c. A comparison of figure 18a with 18b demonstrates the effect of  $C'_D (= \Delta C_{TM} - C_{TM})$  on the thrust, while a comparison of figure 18b and c illustrates the effect of  $C'_L (= C_{LT} - \Delta C_{LT})$  on the total lift. Note the strong influence of  $\alpha$  on the curvature of the  $C_{LT} = \text{constant}$  lines, especially at high  $C_{LT}$  or  $\Delta C_{LT}$  values. Here, because of wing stall,  $\alpha$  can no longer keep the lift at a constant value when  $c_\mu$  is decreasing. At angles of attack approaching stall, at stall, and beyond,  $c_\mu$  must finally increase again to compensate for the loss in lift increase with increasing  $\alpha$ .

Note also that it would have been impossible to deduce confirmation of the thrust hypothesis from any of these three figures. Only in the range of, let us say,  $\alpha = \pm 4^\circ$ , the constant-lift lines approach the 100% thrust recovery slope. This is due to the fact that over this  $\alpha$  range the profile drag as a function of angle of attack is practically constant and that, as we saw previously, at  $\theta = 55^\circ$  (see figure 11) and larger  $\Delta C_{LT}$  values, the drag  $\Delta C_{DT}$  due to blowing does not change (100% thrust recovery).

In figure 19a, figures 11 and 18a are superimposed. As the test data in reference 4 for  $\alpha = 0$  ( $\theta$  changing) are given as  $\Delta$  values, the test data for  $\theta = 55$  ( $\alpha$  changing), however, as absolute values, the  $\Delta C_{TM}$  values of figure 11 had to be converted to  $C_{TM}$  values. This was done by assuming that both tests were run at the same wind-tunnel speed and that therefore the drag  $C'_D$  recorded in figure 9 of reference 4 is also the value by which  $\Delta C_{TM}$  can be converted to  $C_{TM} = \Delta C_{TM} - C'_D$ .

Figure 19a shows that along the  $\Delta C_{LT} = 3$  line at point A, a decrease in blowing would require an increase of the jet-deflection angle beyond  $\theta = 55^\circ$ , where the thrust recovery is no longer 100%. If, however,  $\alpha$  is increased instead of  $\theta$ , a lift coefficient of 3 can be maintained at full thrust recovery down to very appreciably lower rates of blowing, corresponding at least to point B. The very best operating point would actually be at C, where the required lift ( $C_{LT} = 3$ ) is obtained with the

optimum thrust ( $C_{TM} = 0.175$ ) at the lowest possible work expended for blowing. The reason that curve ACB is located below the 100% thrust-recovery line through point A is believed to be as follows: when at point A ( $\theta = 55^\circ$ ,  $\alpha = 0^\circ$ )  $\alpha$  is decreased, the lift component of  $c_\mu$  is increased because of the rotation of the  $c_\mu$  vector by an angle  $\alpha$ . This, due to the condition of  $C_{LT} = \text{constant} = 3$ , requires  $c_\mu$  to be reduced, whereby the drag of the jet-flapped wing is reduced simultaneously. On the other hand, increasing  $\alpha$  leads to another enhancement in lift which leads to a further drag reduction when annulled. Besides the lift increase,  $\alpha$  also causes the drag to rise, but this increase in drag is small as long as  $\alpha$  is small ( $\alpha \leq 8^\circ$ ). In our case, line ACB is located below the 100%-thrust-recovery line, since the drag reduction due to the reduced blowing rates is larger than the drag increase due to  $\alpha$ . At point B, both effects are cancelling each other and beyond B, the drag due to  $\alpha$  dominates.

In figure 19b, a superposition of figures 11 and 18b, the changes in drag, thrust, and lift are those due exclusively to blowing. The above discussed reduction in drag due to increasing  $\alpha$  at constant lift coefficients is more obvious at larger  $c_\mu$  values (compare, for example, the  $C_{LT} = 4$  curves in figure 19a and b). Otherwise, both figures convey the same information.

### 3.2 Most Economical Operation at Angles of Attack

Figures 19a and b suggest that for the most economical operation of jet-flapped wings, the use of the angle of attack is as important as the jet-deflection angle. For the pure jet-flapped wing under consideration here, complete thrust recovery, at  $C_{LT} = 3$  for example, can be ascertained for  $\theta \leq 55^\circ$  and  $\alpha = 0^\circ$  or for  $\alpha \leq 10^\circ$  and  $\theta = 55^\circ$ . The useful angle of attack range seems to be almost constant, except perhaps for a slight decrease at large  $C_{LT}$  values.

In general, a jet-flapped wing operates most economically if it produces a certain desired lift at the lowest possible drag and the least amount of blowing. For a desired lift coefficient of  $C_{LT} = 3$ , for example, the point C (figure 19a) meets these requirements for the pure jet-flapped wing of reference 4; the optimum values for  $\theta$  and  $\alpha$  seem to be  $\theta \approx 60^\circ$  and  $\alpha \approx 8^\circ$  respectively. A line of most economical operation or an "operating line" could be drawn so that it connects the points at which the  $C_{LT} = \text{constant}$  lines for changing  $\alpha$  intersect (see point B, for example,) the 100%-thrust-recovery line or, still better, where a tangent, parallel to the straight portion of the  $\Delta C_{LT} = 3$  line touches the curve ACB at C.

In comparing the operating lines of a jet-flapped wing at zero angle of attack (see section 2.6.1) with the one discussed above, one finds that the reductions in blowing rates due to  $\alpha$  are very appreciable (50% for  $\Delta C_{LT} = 3$ , see point A and B of figure 19a). If the amount of blowing required for the production of thrust,  $c_{\mu T}$ , is smaller or equal to that required for lift,  $c_{\mu L}$ , the use of  $\alpha$  for producing lift is essential. If  $c_{\mu T}$  is greater than  $c_{\mu L}$  at point B (figure 19a), but smaller than the amount of blowing required at zero  $\alpha$  and optimum  $\theta$  (point A), the full use of  $\alpha$  is still advantageous, especially if only that portion of the jet-engine exhaust which is required solely for lift production is expelled through the trailing edge slots. If, however,  $c_{\mu T}$  is greater than the  $c_{\mu L}$  required at  $\alpha = 0$  (point A in figure 19a), beneficial effects from the use of  $\alpha$  can only be derived if the jet engine exhaust through the wing trailing edge slots is limited strictly to that needed for the production of the desired lift. The benefits in this case are indirect and of a practical nature; they include reduced pressure losses, less structural weight, and less occupied wing space because of lower duct-flow velocities and cross-sectional area. Almost the same benefits can be insured if the mass flow through the trailing edge slots is enhanced so that the desired lift is obtained by the use of  $\theta$  alone (keeping  $\alpha = 0$ ). This scheme may well be worthwhile in view of simplifying the pilots' maneuvers during take-off.

### 3.3 The Jet-Flapped Wing and STOL

This consideration is rather hypothetical because of the high-aspect ratio ( $AR \approx 20$ ) of the jet-flapped wing represented in the "Characteristics" of figure 19a. Nevertheless, if a truly three-dimensional jet flap is similarly evaluated later, the effect of aspect ratio can be deduced on the STOL potential of jet-flapped wings.

#### 3.3.1 Lift Analysis

In reference 12, averaged thrust coefficients at take-off and cruise of fighter aircraft, airliners and trainers are shown to be:

$$\text{take-off: } c_{\mu T} = 0.5$$

$$\text{cruise: } c_{\mu T} = 0.025$$

Let us now imagine that such a conventional aircraft is to be converted into a STOL aircraft by means of the jet-flap principle. The take-off run is to be shortened to 1/6 of its conventional take-off distance. Weight and thrust are assumed to be the same for both aircraft. Since the lift at take-off must be the same for both aircraft,

$$C'_L \frac{\rho}{2} V'^2_T \cdot S_w = C_{LT} \frac{\rho}{2} \cdot V_T^2 \cdot S_w = C_{LT} \frac{\rho}{2} \frac{V'^2_T}{6} \cdot S_w,$$

assuming constant acceleration. Consequently,  $C_{LT} = 6 C'_L$ , which requires  $c_\mu$  to become  $c_\mu = 6 c_{\mu T} = 3$ . Suppose  $C'_L = 1.2$ , the required take-off lift  $C_{LT}$  would have to become  $C_{LT} = 7.2$ .

If the pure jet-flap of figure 19a were to be used at  $\theta = 60^\circ$ ,  $\alpha = 0^\circ$ , and  $c_\mu = 3$ ,  $C_{LT}$  would be found from equation (2.6) as

$$C_{LT} = \Delta C_{LT} = \sqrt{4.1 \cdot 0.73 \cdot 3} = 6.15$$

This lift would be too small to get the aircraft off the ground at the prescribed take off point. The lift could be increased to  $C_{LT} = 7.2$  by either increasing the engine thrust so that  $c_\mu$  is raised from 3 to 4.1 (a 37% thrust increase) or by choosing a jet-flapped wing, which at  $\theta = 60^\circ$ ,  $\alpha = 0^\circ$ , and  $c_\mu = 3$ , produces a higher lift. Such aerofoils are obviously those with jet-control flaps and their higher lift values are due to a higher K, as is shown in figure 13. The K required here follows from equation (2.6) for  $C_{LT} = 7.2$  as  $K = 4.8$ . Either wing, the one for the upper surface or the one for symmetrical blowing over the jet-control flap, would be suitable.

If the angle of attack, in addition to  $\theta = 60^\circ$ , were used for lift production, the required  $c_\mu = 4.1$  for the pure jet-flapped wing of figure 19a could be reduced, it seems, to about half the above value. This leaves two alternatives: (1) to expell the entire engine mass flow through the trailing edge slots of the wings irrespective of how much of it is actually required for lift production, or (2) to expell only that portion of the engine mass flow through the slots which produces the required lift. The remaining portion of the engine mass flow, and eventually during cruise the entire mass flow, is expelled in the conventional way.

### 3.3.2 Thrust Analysis

At the take off point, besides lift, enough thrust must be supplied to permit a desired rate of climb. How much thrust is available for climb depends on the total drag of the jet-flap version at take off. This total drag can be calculated from equation (2.4), if  $C_1$  is known. For the pure jet-flapped wing of figure 19a,  $C_1$  was found to be 0.55, and the total drag then becomes

$$C_{DT} = \frac{0.55}{4.1^2} \cdot 7.2^2 = 1.70$$

or

$$C_{TM} = 3 - 1.70 = 1.30$$

The maximum angle of climb at constant take off speed,  $V_T$ , follows then from

$$\tan \beta = \frac{1.30}{7.2} \text{ as } \beta \approx 10^\circ.$$

A 50 foot obstacle could be cleared at a distance of approximately 300 feet, this includes a 20 foot transition region. Shorter distances would require corresponding increases in engine thrust. Note that employment of  $\alpha$  for lift production does not change the total drag ( $C_{DT} = 1.70$ ) as long as one does not operate above the operating line.

### 3.4 The Total Drag as a Function of $c_\mu$

#### 3.4.1 Jet Deflection Angle $\theta = 55^\circ$

If one plots the total drag versus  $c_\mu$  for the pure jet-flapped wing at  $\theta = 55^\circ$  with  $\alpha$  as the parameter, figure 20 is obtained. We see that, the total drag follows the relationship

$$\Delta C_{DT} = a(\alpha) c_\mu, \quad (3.1)$$

as in figure 14, at least as long as  $c_\mu \leq 1.0$ . Obviously, per degree,  $\Delta C_{DT}$  increases more strongly with  $\alpha$  than with  $\theta$ . Consequently,  $d(\Delta C_{DT})/d c_\mu$  must decrease more rapidly with  $\alpha$  than with  $\theta$ . This is shown in figure 21 for the pure jet-flapped wing. For jet-flapped wings with upper surface or symmetrical blowing, the  $d(\Delta C_{DT})/d c_\mu$  for  $\alpha = 0$  are shown also.

If we plot the function  $a(\alpha)$  versus  $\sin \alpha$ , the lower curve of figure 22 is obtained. If we plot  $a(\alpha)$  versus  $\sin^2 \alpha$ , the upper curve results; these plots suggests that over the useful  $\alpha$ -range of  $0 < \alpha < 10$ ,  $a(\alpha)$  may be considered as a linear function of  $\sin^2 \alpha$ , or

$$d(a(\alpha))/d \sin^2 \alpha = C_2 \quad (3.2)$$

where  $C_2$  for this specific wing is equal to 7.7. From equation (3.2) it follows that

$$a(\alpha) + C = C_2 \sin^2 \alpha. \quad (3.3)$$

Since for  $\alpha = 0$ ,  $C = -a(0)$  we get

$$a(\alpha) = a(0) + C_2 \sin^2 \alpha, \quad (3.4)$$

and

$$\Delta C_{DT} = (a(0) + C_2 \sin^2 \alpha) c_\mu. \quad (3.5)$$

Substituting the numerical values for  $a(0)$  and  $C_2$ , we obtain the total drag of a jet-flapped wing at  $\theta = 55^\circ$  ( $c_\mu \leq 1$ ) as a function of the angle of attack over its practically useful range ( $0 < \alpha < 10^\circ$ ). It is

$$\Delta C_{DT} = (0.365 + 7.7 \sin^2 \alpha) c_{\mu}, \quad (3.6)$$

or since  $\Delta C_{TM} = c_{\mu} - \Delta C_{DT}$ , we get

$$\begin{aligned} \Delta C_{TM} &= c_{\mu} [1 - (a(0) + C_2 \sin^2 \alpha)] \\ &= c_{\mu} [1 - (0.365 + 7.7 \sin^2 \alpha)]. \end{aligned} \quad (3.7)$$

To demonstrate the applicability of the equations derived above for the total drag of jet-flapped wings, let us consider point A of figure 19b. The line through A and the origin represents the line  $\theta = 55^\circ$  and  $\alpha = 0^\circ$ . The total drag change along this line can be calculated from either

$$\Delta C_{DT} = C_1 \sin^2 \theta c_{\mu} = a(\theta) c_{\mu}, \quad (2.5)$$

or

$$\Delta C_{DT} = (a(0) + C_2 \sin^2 \alpha) c_{\mu}, \quad (3.5)$$

which means that

$$C_1 \sin^2 \theta = (a(0) + C_2 \sin^2 \alpha) \quad (3.8)$$

or

$$a(0) = a(\theta); \text{ (as } \alpha = 0). \quad (3.9)$$

Knowing now  $\Delta C_{DT}$  at A from  $\Delta C_{DT} = a(\theta) c_{\mu}$ , we could find  $\Delta C_{LT}$  at A from

$$\Delta C_{DT} = \frac{C_1}{K^2} \Delta C_{LT}^2.$$

Inserting for  $\Delta C_{LT}$  another value, say 2, we could find point B, the point where the  $\Delta C_{LT} = 2$  line - if still straight, indicating 100% thrust recovery - intersects the  $\theta = 55^\circ$ ,  $\alpha = 0^\circ$  line.

In order to find  $\Delta C_{DT}$  after a change in  $\theta$  and  $c_{\mu}$ , but at  $\alpha = 0$ , the equation

$$\Delta C_{DT} = C_1 \sin^2 \theta c_{\mu} \quad (2.5)$$

is to be used; for any changes of  $\alpha$  and  $c_{\mu}$  at  $\theta = 55^\circ$ , the equation

$$\Delta C_{DT} = (a(\theta) + C_2 \sin^2 \alpha) c_{\mu} \quad (3.5)$$

predicts the total drag along any line chosen. Note that the  $\Delta C_{LT} = \text{constant}$  lines obtained by changing  $\theta$  at  $\alpha = 0^\circ$  are not identical with the  $\Delta C_{LT} = \text{constant}$  lines resulting from varying  $\alpha$  at  $\theta = 55^\circ$ . Both, however, go through point A.

It should be kept in mind that the above equations apply only for that part of the "characteristics" where the thrust recovery is complete. Fortunately, it is also this part which is of greatest practical interest for the most economical jet-flap operation.

### 3.4.2 Arbitrary Jet-Deflection Angles

If the jet-deflection angle  $\theta = 55^\circ$ , on which the only available test results for varying angles of attack are based, were changed to any other angle,  $\theta = 33^\circ$ , for example, what would be the effect on the total drag? In general, equation (3.5) applies:

$$\Delta C_{DT} = [a(0) + C_2 \sin^2 \alpha] c_\mu \quad (3.5)$$

where  $a(0)$  could be immediately determined from equation (3.8) as

$$a(0) = a(\theta) = 0.55 \sin^2 33 = 0.164$$

or directly from figure 15. If we assume that  $C_2$  is not affected by a change in  $\theta$ , which in other words means that in figure 22, the line  $\theta = 33^\circ$  is parallel to that shown for  $\theta = 55^\circ$ , then  $\Delta C_{DT}$  could be obtained from

$$\Delta C_{DT} = [0.164 + 7.7 \sin^2 \alpha] c_\mu. \quad (3.10)$$

This equation is evaluated in figure 23. It was obtained by combining the lower part of figure 20 with figure 11 so that the  $\alpha = 0$  line was superposed over the  $\theta = 33^\circ$  line and the vertical distances between the  $\alpha$  lines of figure 20 were retained in figure 23. This semi-analytical figure would, of course, have to be checked against test results for  $\theta = 33^\circ$  and varying angles of attack. Also the experimental constant-lift lines for varying would have to be added.

On comparison of figure 23 with figure 19b, for example, it becomes obvious that this small jet-deflection angle is not insuring economical jet-flap operation, at least as long as  $c_{\mu T} \leq c_{\mu L}$ . The rate of blowing is much too high for achieving a lift coefficient of  $\Delta C_{LT} = 3$ , and the use of  $\alpha$  up to the point of diminishing returns, where the onset of stall is felt, cannot compensate for the loss in economy inflicted by not making the fullest use of the lifting capabilities of the jet-deflection angle.

How realistic the assumption of  $C_2 = \text{constant}$ , which led to figure 23, really is can only be answered by further tests.

### 3.5 Construction of A Jet-Flap "Characteristics"

Below the operating line of a "characteristics", where along  $C_{LT} =$  constant lines the thrust recovery is complete, the values of  $C_1$ ,  $C_2$ , and  $K$  were found to be constants. If these constants are known for a particular jet-flapped wing, its "characteristics" can be artificially constructed, or an existing incomplete "characteristics" can be supplemented.

Pick point A in Fig. 19a. Its total drag follows from equation (2.5) or (3.5), its total lift from equation (2.7). Inserting any other lift value into equation (2.7) furnishes the corresponding total drag and permits this  $C_{LT} =$  constant line to be added to the "characteristics". Similarly, lines of constant  $\theta$  or  $\alpha$  can be added. If any  $\theta$  and  $c_{\mu}$  values are selected at  $\alpha = 0^\circ$ , the total drag follows from equation (2.5); if  $\alpha$  and  $c_{\mu}$  are changed at  $\theta = 55^\circ$ , the total drag is obtained from equation (3.5). In this way, part of a jet-flap "characteristics" can be artificially constructed over which the jet-flapped wing operates most economically.

#### IV. CONCLUSIONS

For truly and quasi two-dimensional jet-flapped wings, the thrust hypothesis is shown to be experimentally true.

Provided that the total lift is kept constant, the jet-flap "characteristics" indicates that the total drag does not change with changing jet-deflection angle and rate of blowing over what can be considered the practical operating range of jet-flapped wings. Within this range, confined by jet deflection angles and angles of attack of less than  $60^\circ$  and  $10^\circ$  respectively, increases in jet momentum thrust are completely recovered as propulsive thrust. In producing lift, the angle of attack is, besides the jet deflection angle, a very powerful means of improving the economy of operation of high aspect ratio jet-flapped wings.

Operation of a jet-flapped wing along the "operating line" for optimum performance and maximum economy, is practical and possible only if merely that portion of the jet engine exhaust is ejected through the wing trailing-edge slots, which, according to the "characteristics", is required for the production of the desired lift. The resulting savings in internal wing space and ducting weight depend very much on the ratio of the jet flap to jet-engine mass flow; elaboration on this question makes real sense only if one considers a low-aspect-ratio jet-flapped wing under STOL take-off conditions. This will be done in a forthcoming report, presenting and discussing three-dimensional jet-flap "characteristics" and their implications on STOL aircraft operation and design.

A jet-flap "characteristics" can be constructed or supplemented if three "constants" relating the total drag to the total lift are known. The thus constructed "characteristics" covers the entire jet-flap operating range, which, on the basis of performance and economy, is solely of practical interest.

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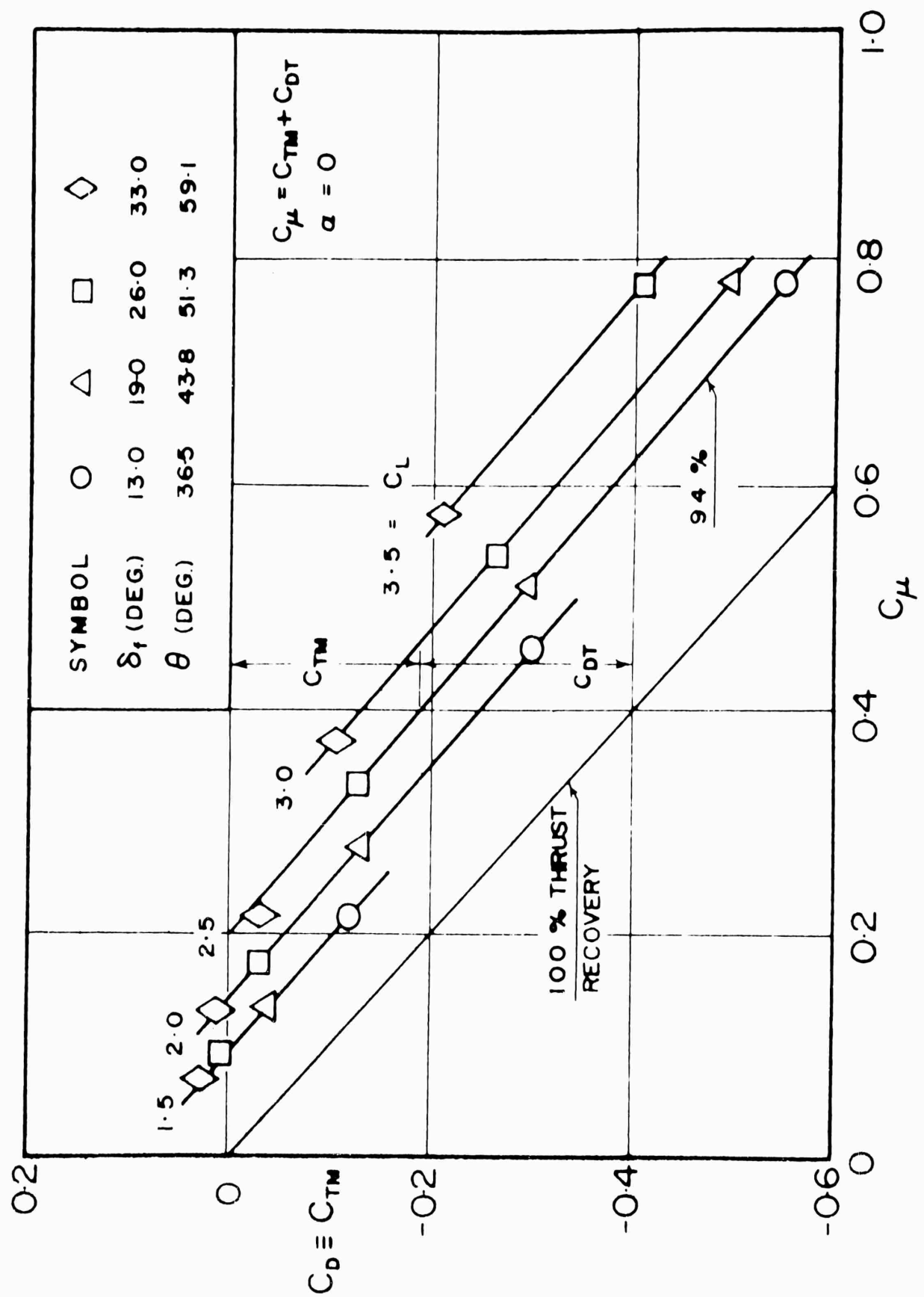


Figure 2. Thrust Recovery and Thrust and Drag Variation at Constant Lift (Test Data of reference 1).

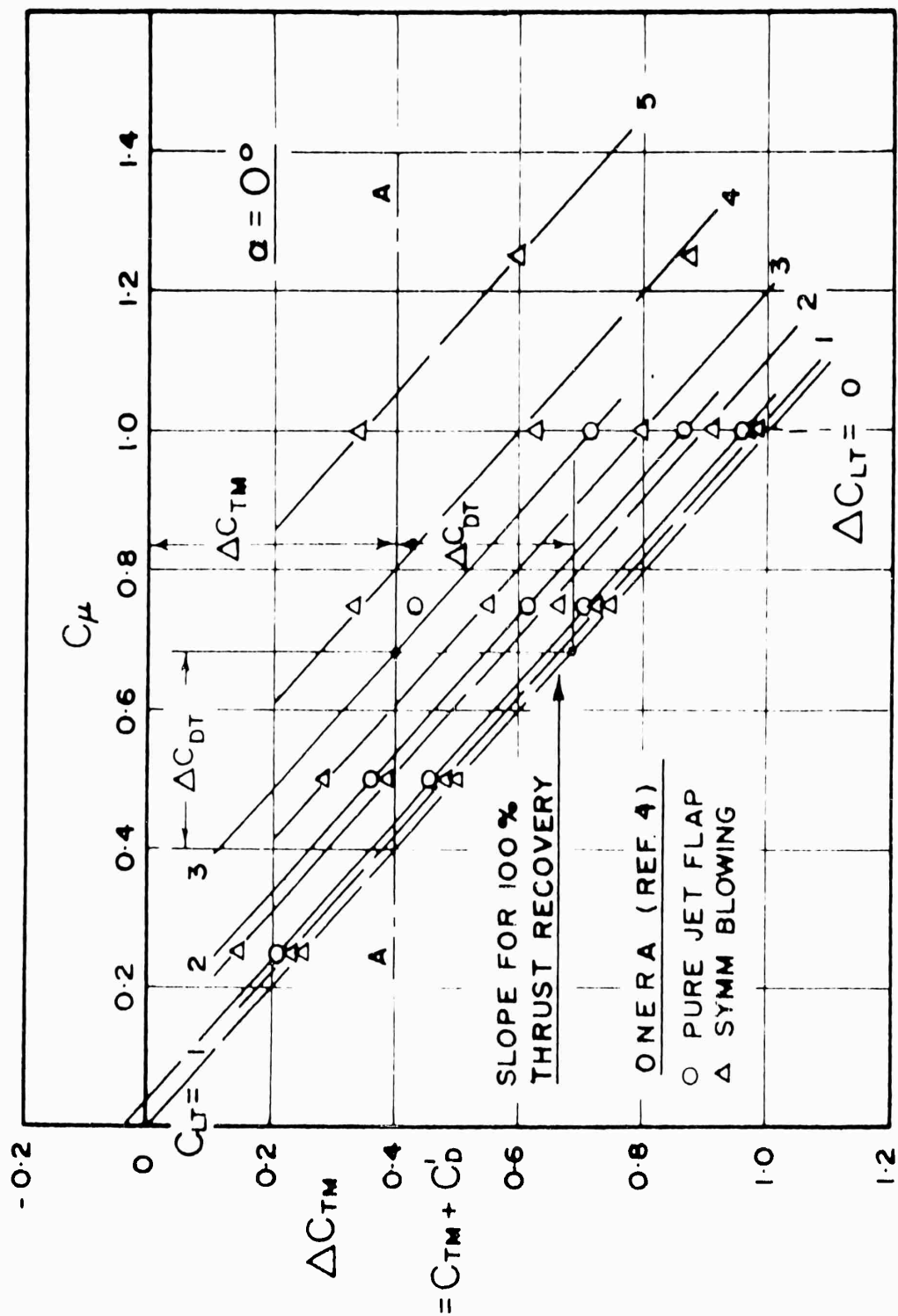


Figure 3. Thrust Recovery and Drag Variation at Constant Lift (Test Data of reference 4)

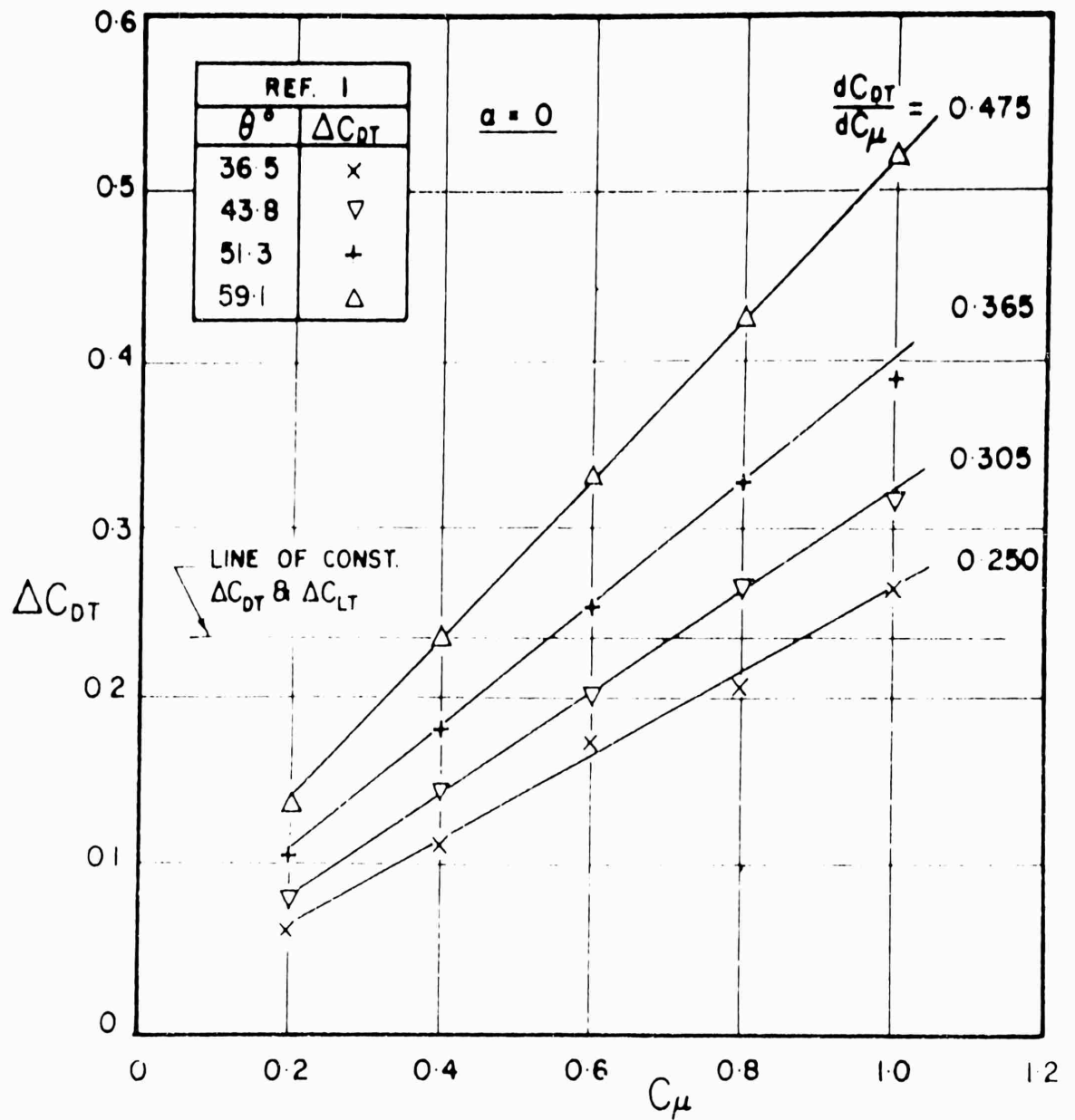


Figure 4. The Total Drag Variation (Due to Blowing) as a Function of Blowing (Test Data of reference 1).

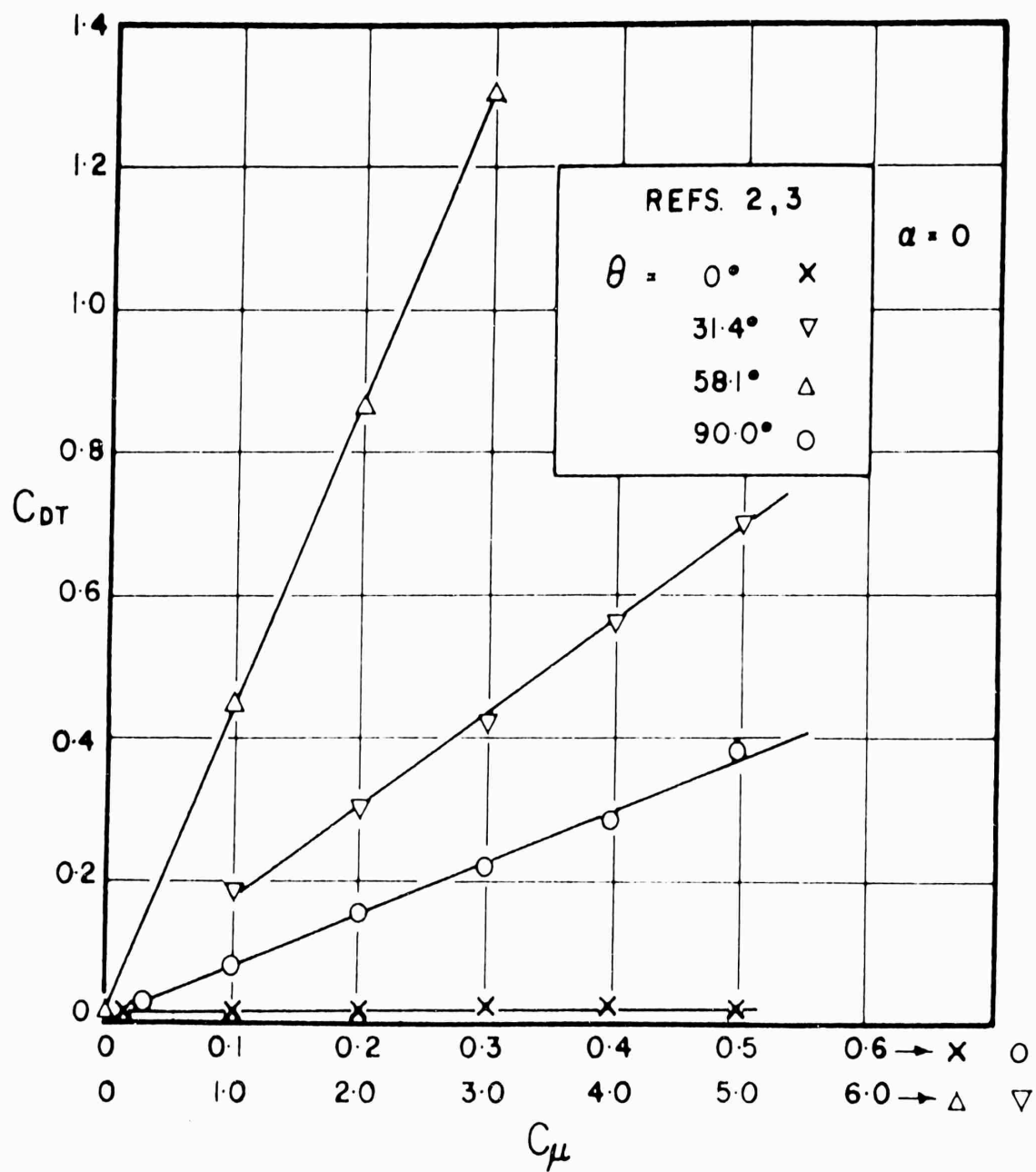


Figure 5. The Total Drag Variation as a Function of Blowing (N. G. T. E. Test Data, reference 2 and 3).

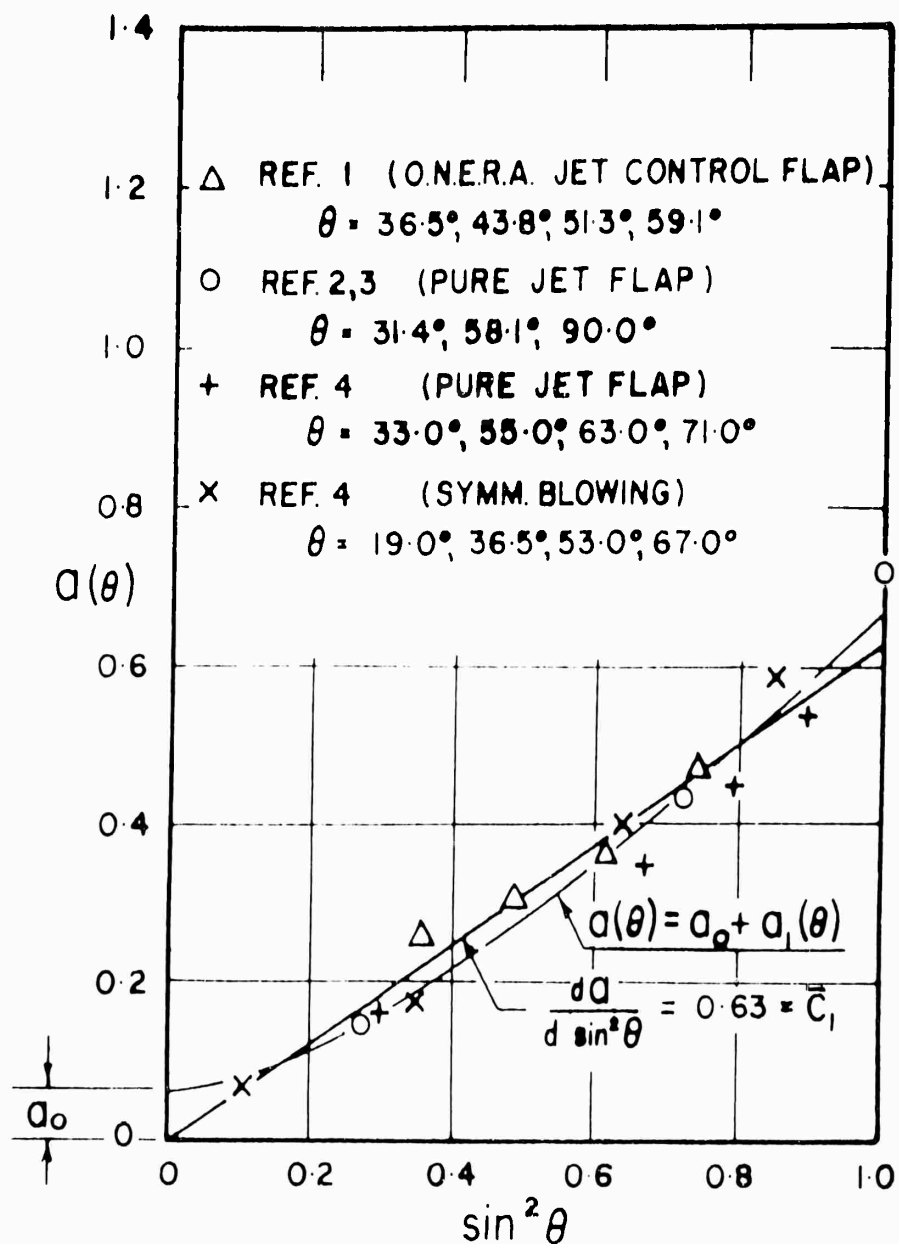


Figure 6. The Factor  $C_1 = da(\theta)/d \sin^2 \theta$ , as Obtained from all Available Quasi-Two-Dimensional Jet-Flap Test Results.

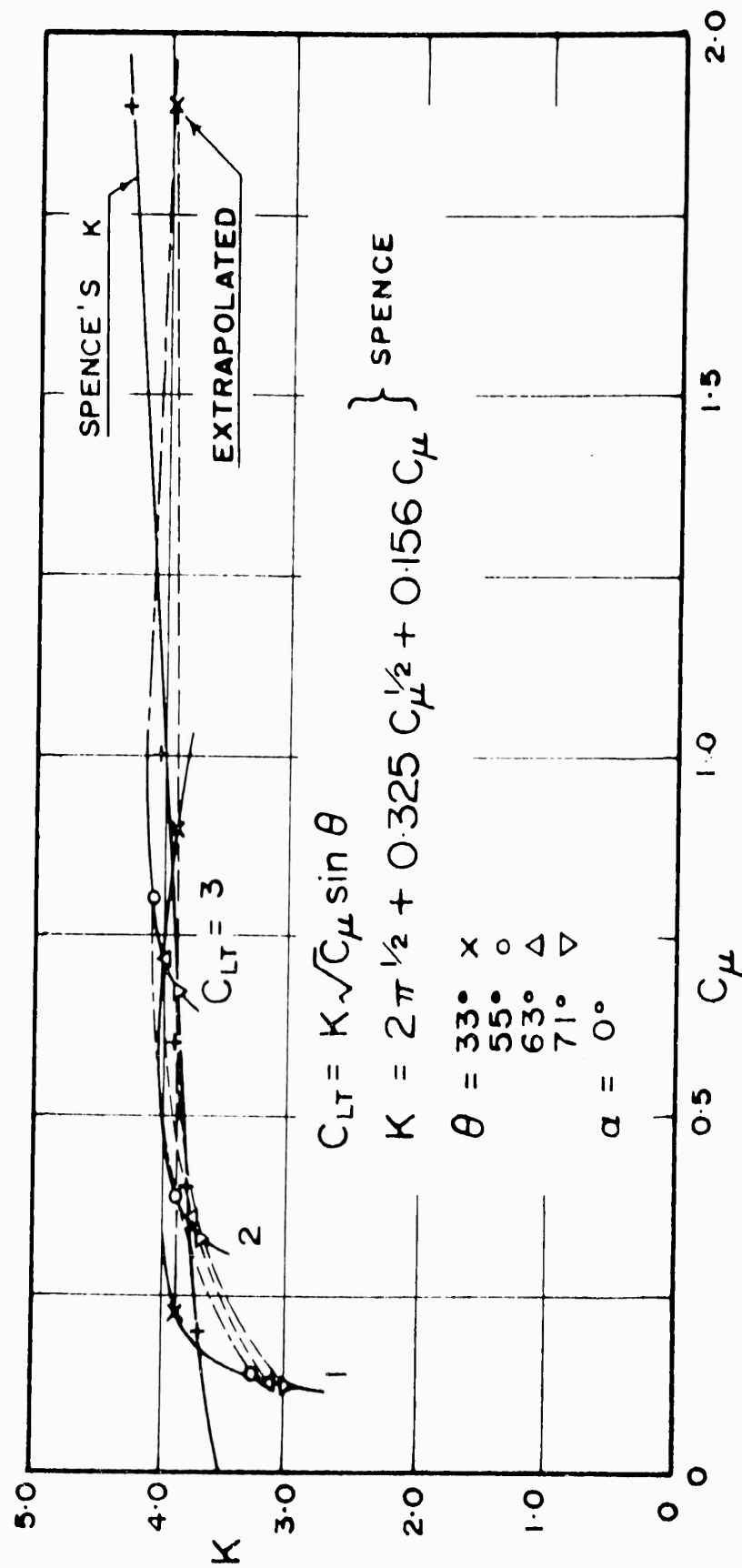


Figure 7. The Factor  $K$  as Obtained from the Pure Jet-Flap Test Results of reference 4.

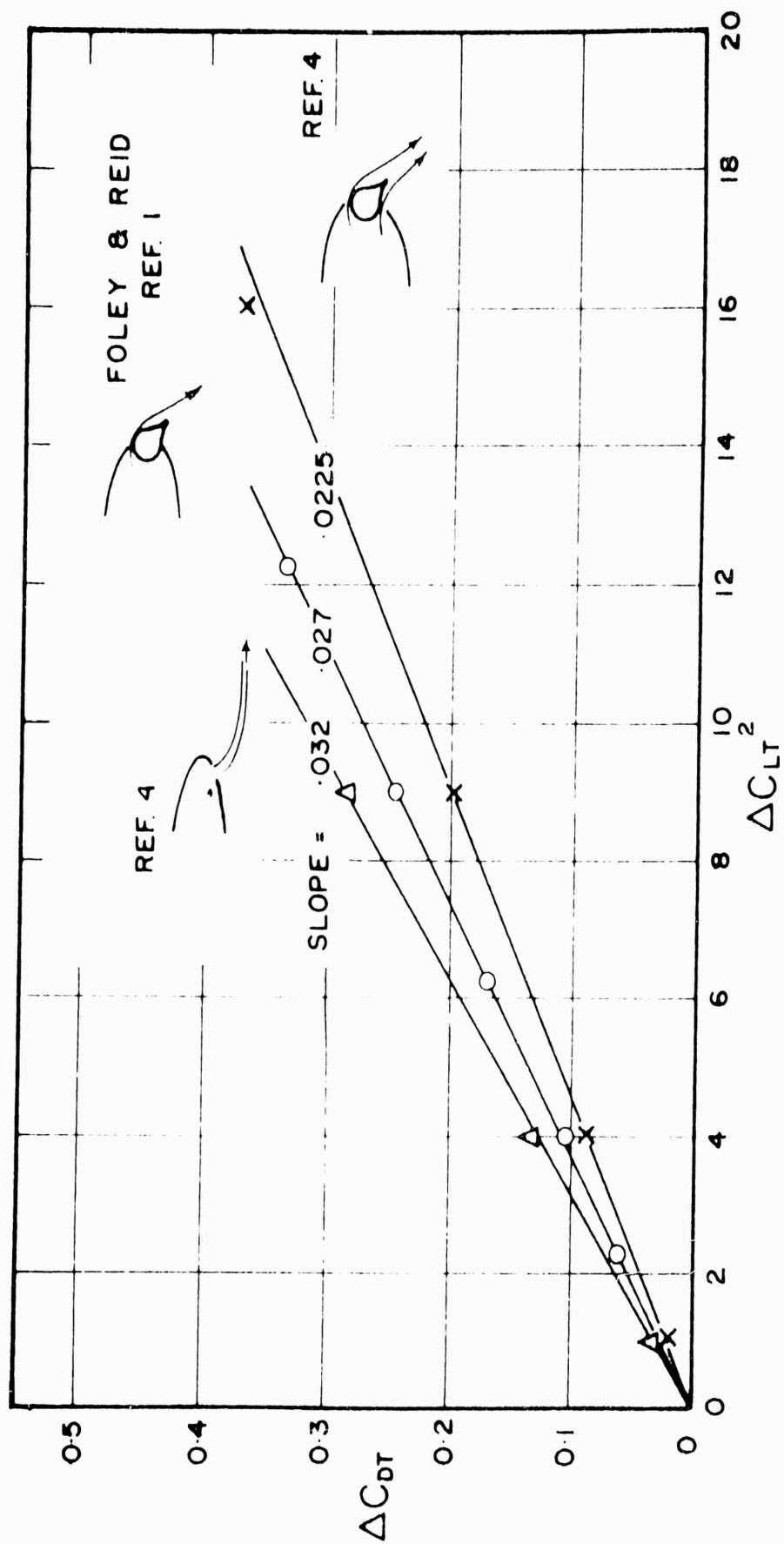


Figure 6. The Constant Slope  $d(\Delta C_D T)/d(\Delta C_L T^2)$  for Three Different Jet-Flapped Wings.

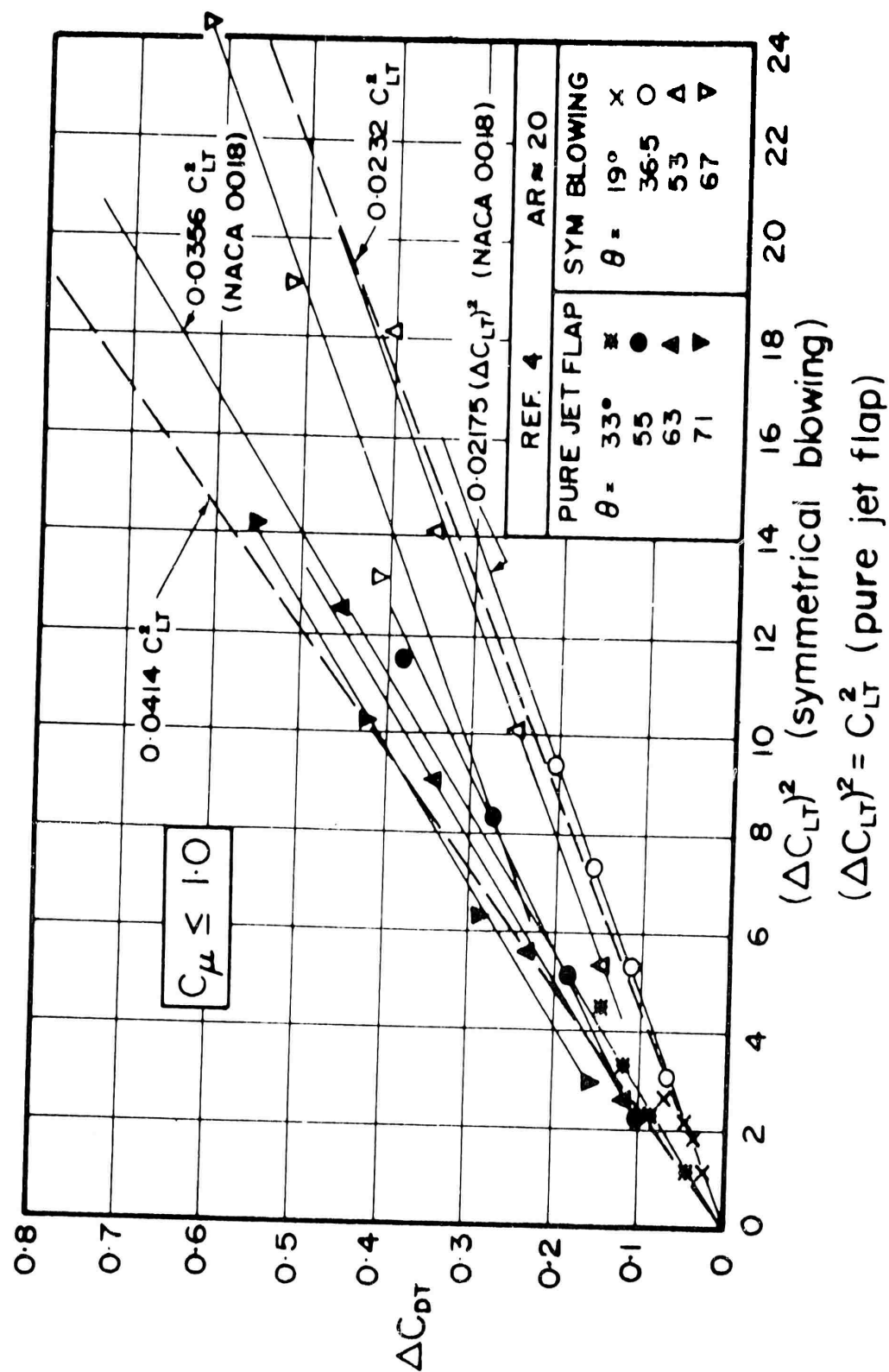


Figure 9. A Total Drag versus Total Lift Squared Plot with the Jet-Deflection Angle as a Parameter (Test Data of reference 4).

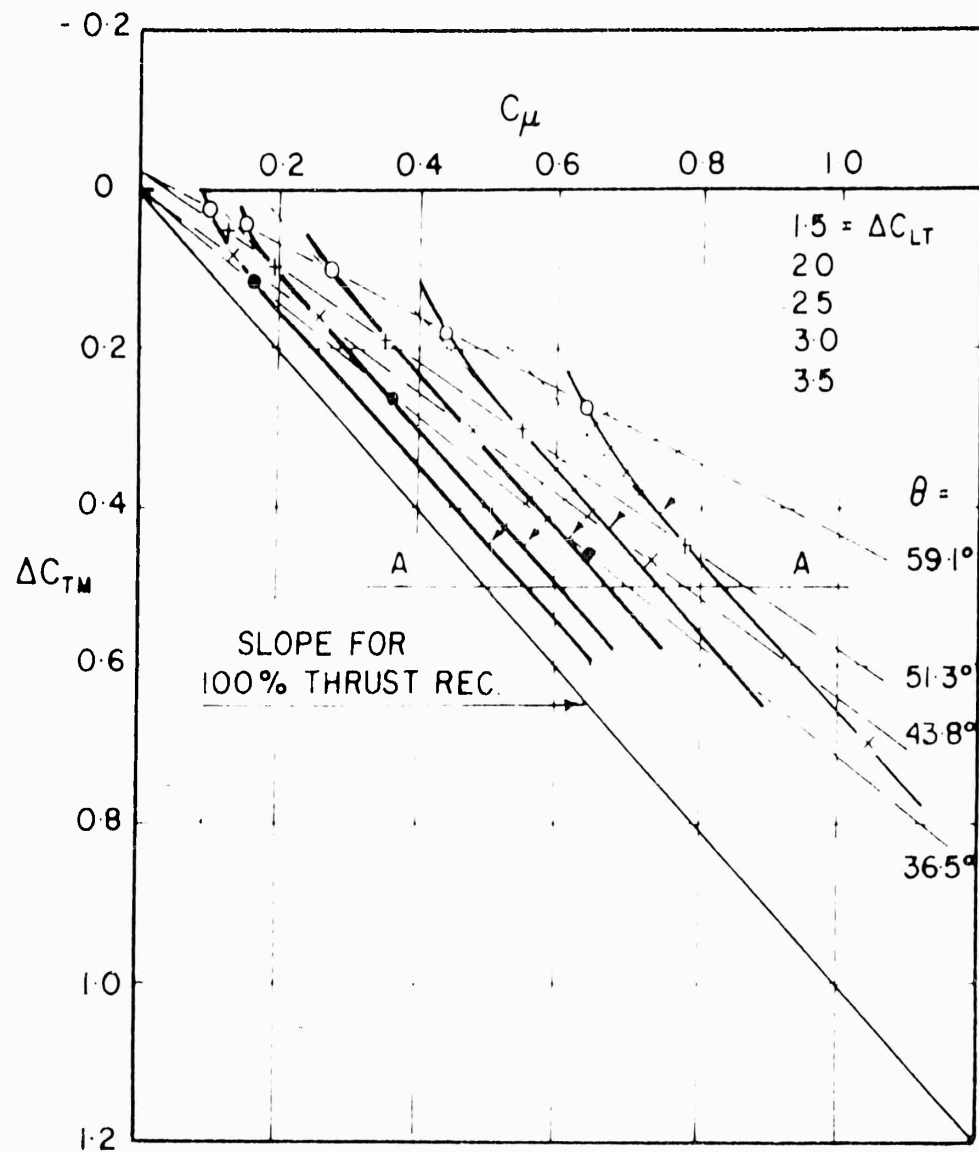


Figure 10. Thrust Recovery and the Real Thrust and Drag Variation as a Function of Lift (Corrected Test Data of Reference 1).

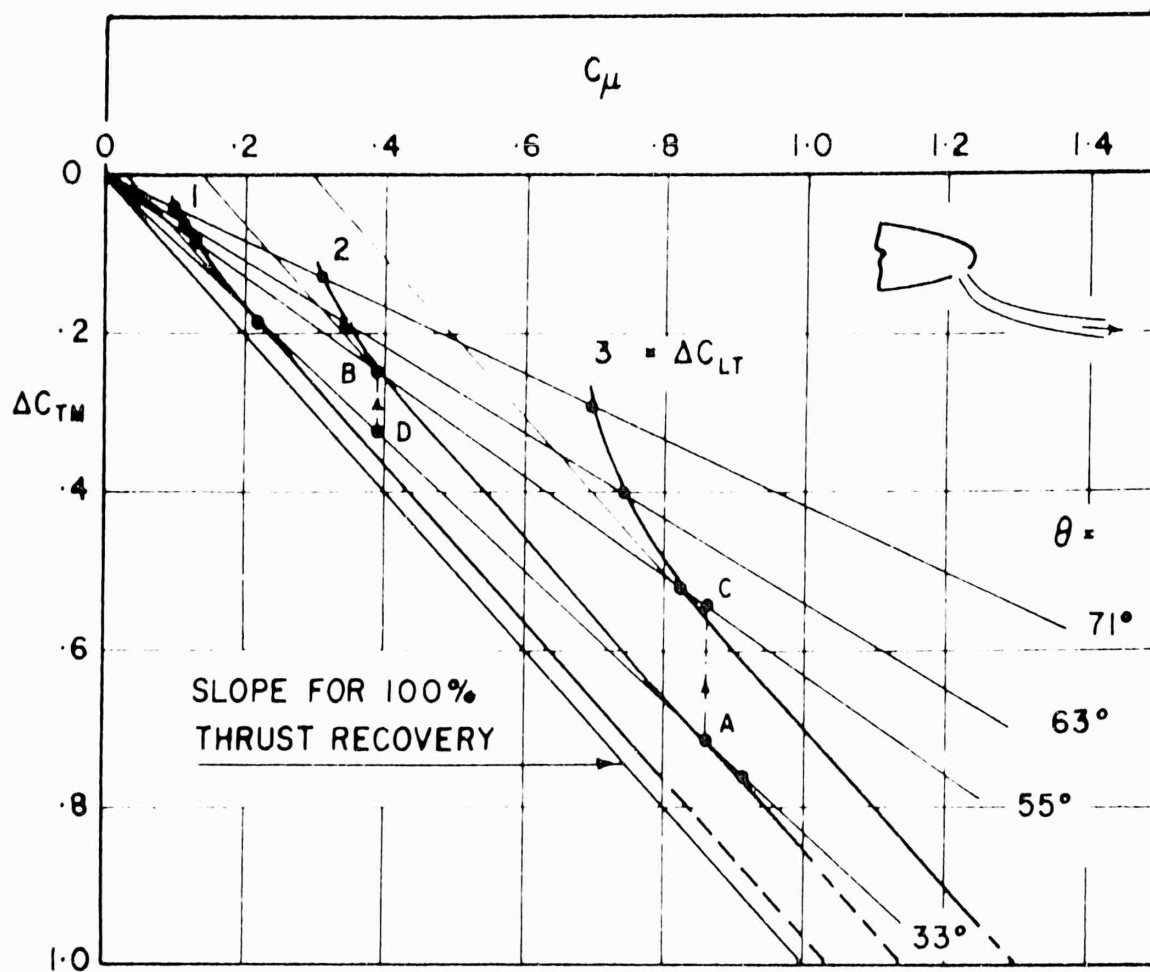


Figure 11. Thrust Recovery and the Real Thrust and Drag Variation at Constant Lift (Test Data of reference 4 - Pure Jet Flap).

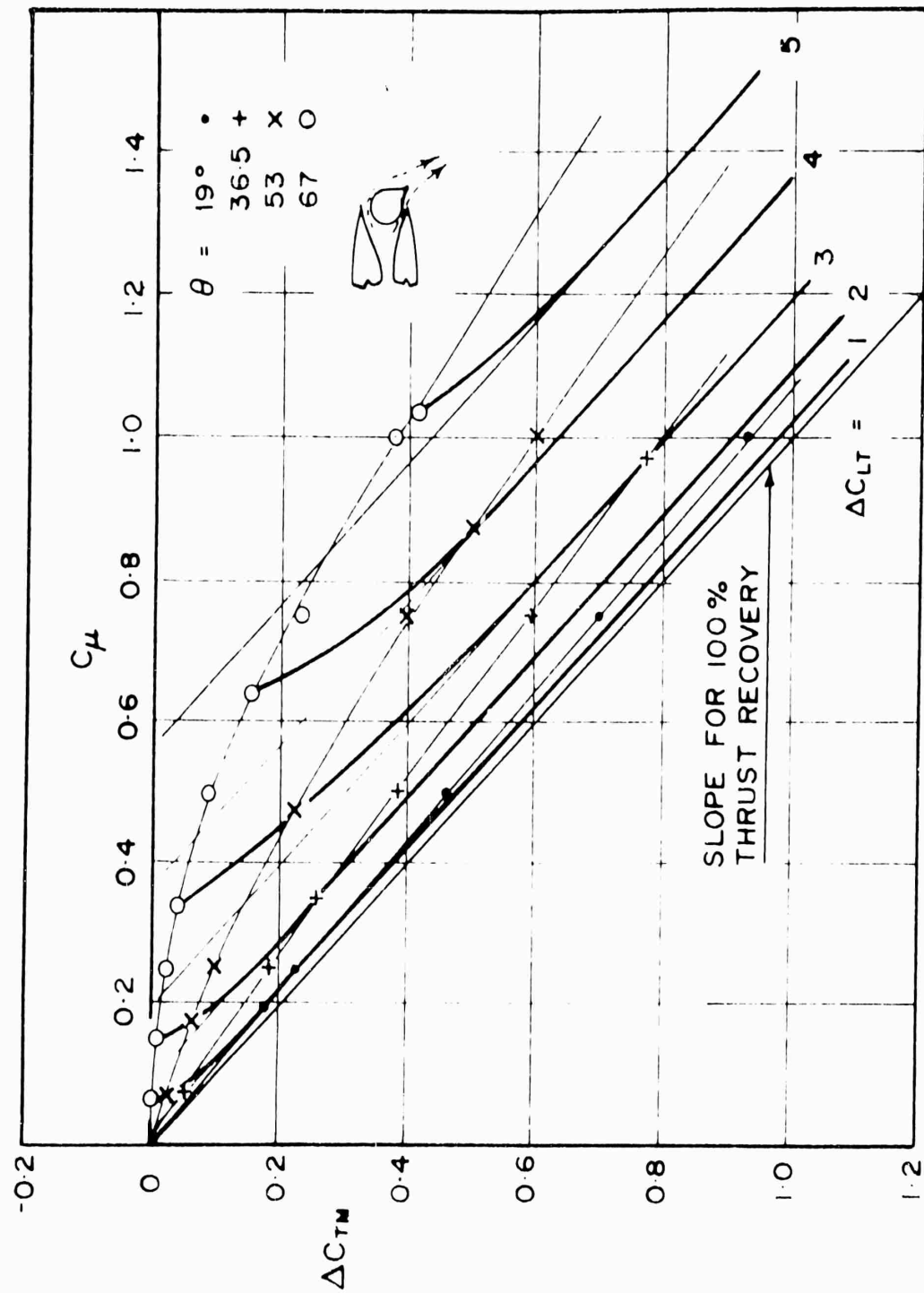


Figure 12. Thrust Recovery and the Real Thrust and Drag Variation at Constant Lift (Test Data of reference 4 - Symmetrical Blowing).

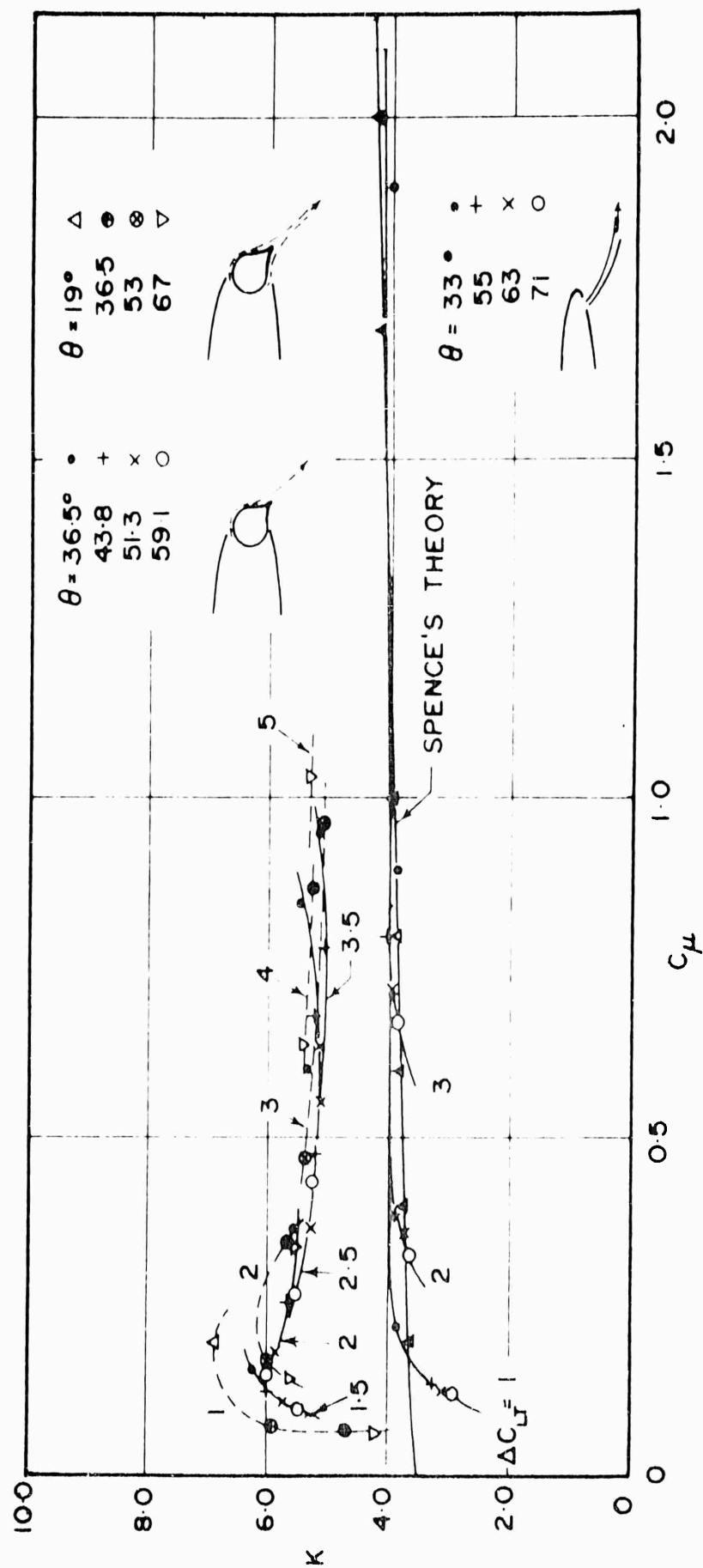


Figure 13. A Comparison of the Factor  $K$  as Obtained for Various Jet-Flap Configurations (Test Data from reference 1 and 4).

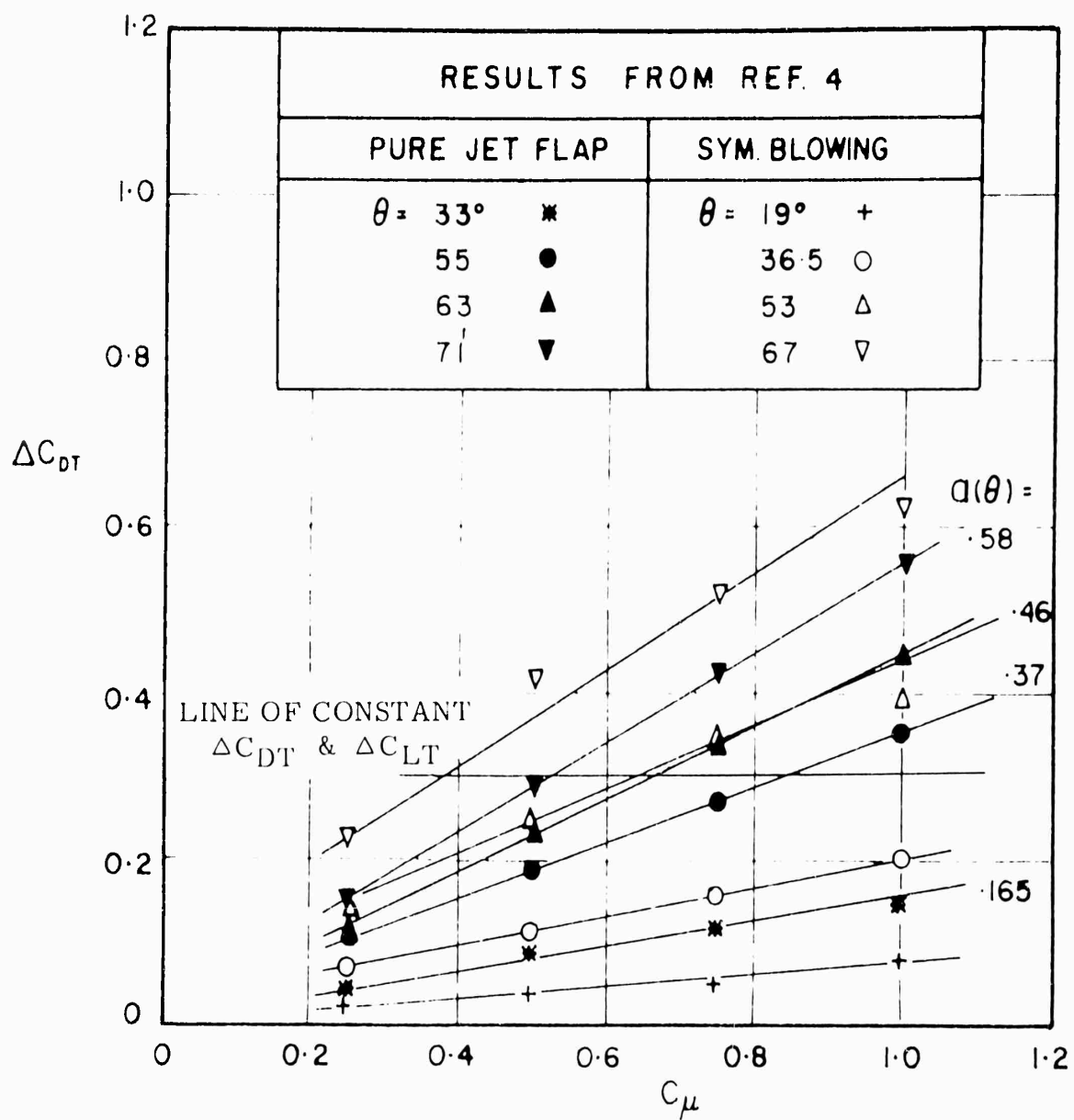


Figure 14. The Total Drag Variation (Due to Blowing) as a Function of Blowing (Test Data of reference 4).

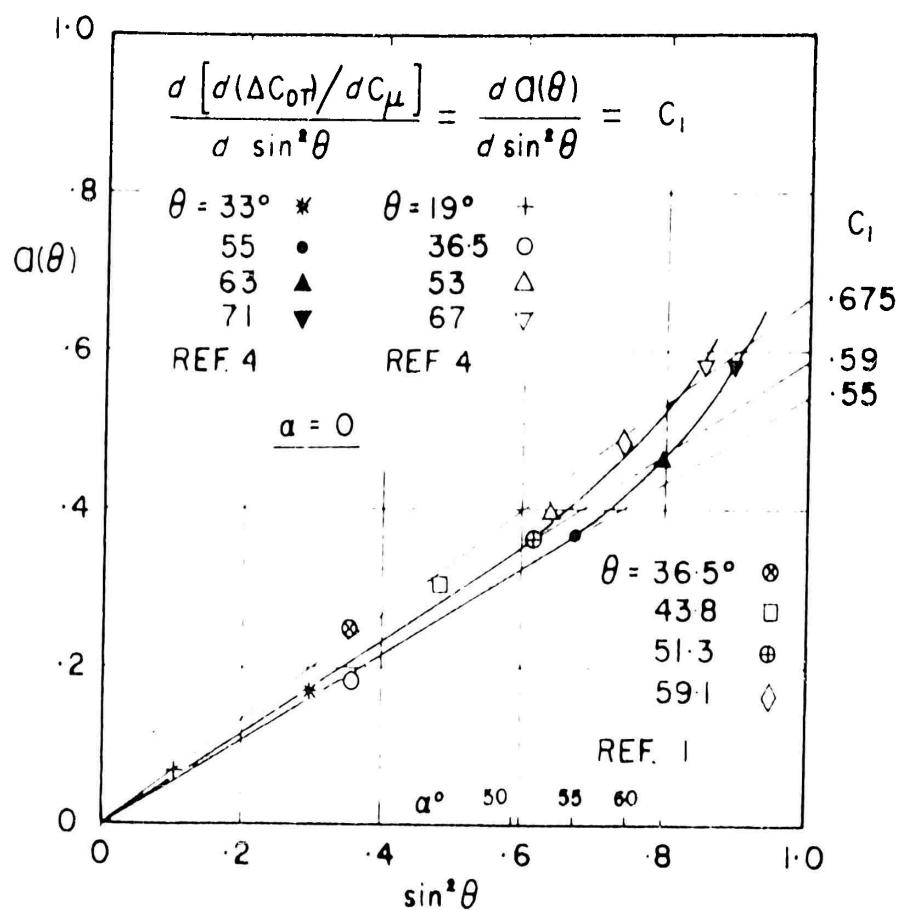


Figure 15. The Factor  $C_1 = d a(\theta)/d \sin^2 \theta$  as Obtained for 3 Different Jet-Flapped Wings.

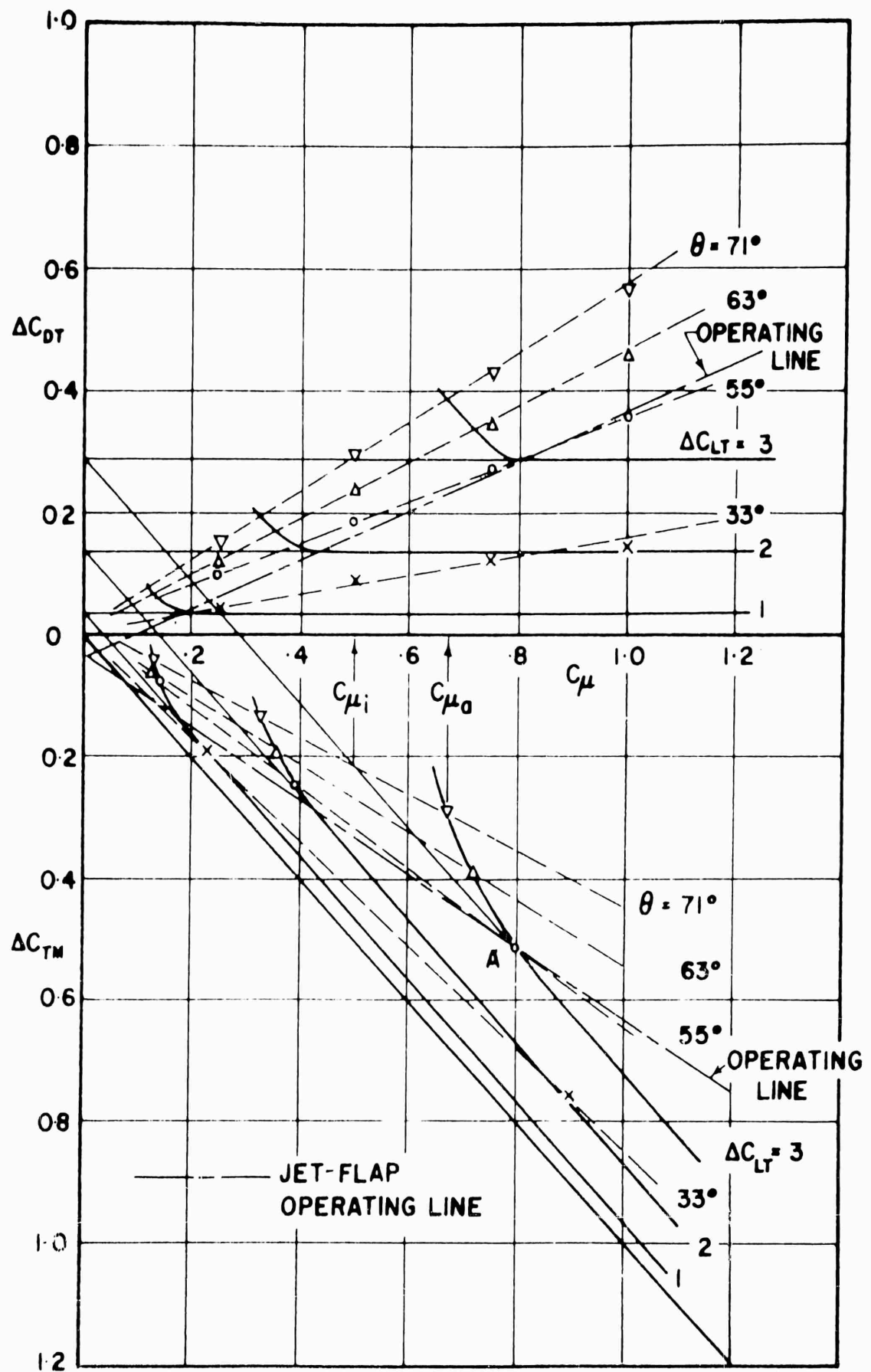


Figure 16. The Jet-Flap Characteristics for a Pure Jet-Flapped Wing at Zero Angle of Attack (Test Data of reference 4).

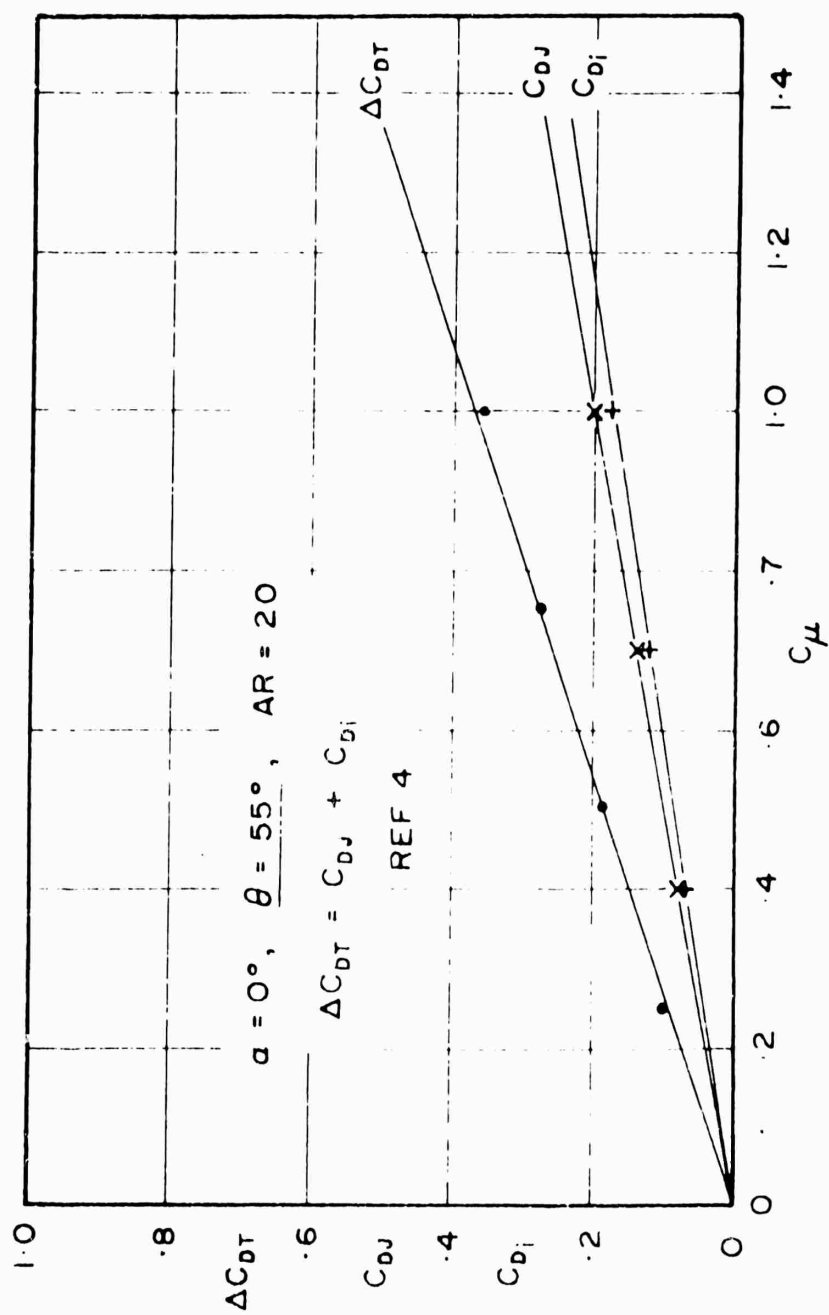


Figure 17a. The Variation of the Calculated Jet Drag (Eq. 2.26) and Induced Drag and Their Comparison with the Total Drag (Test Data of reference 4).

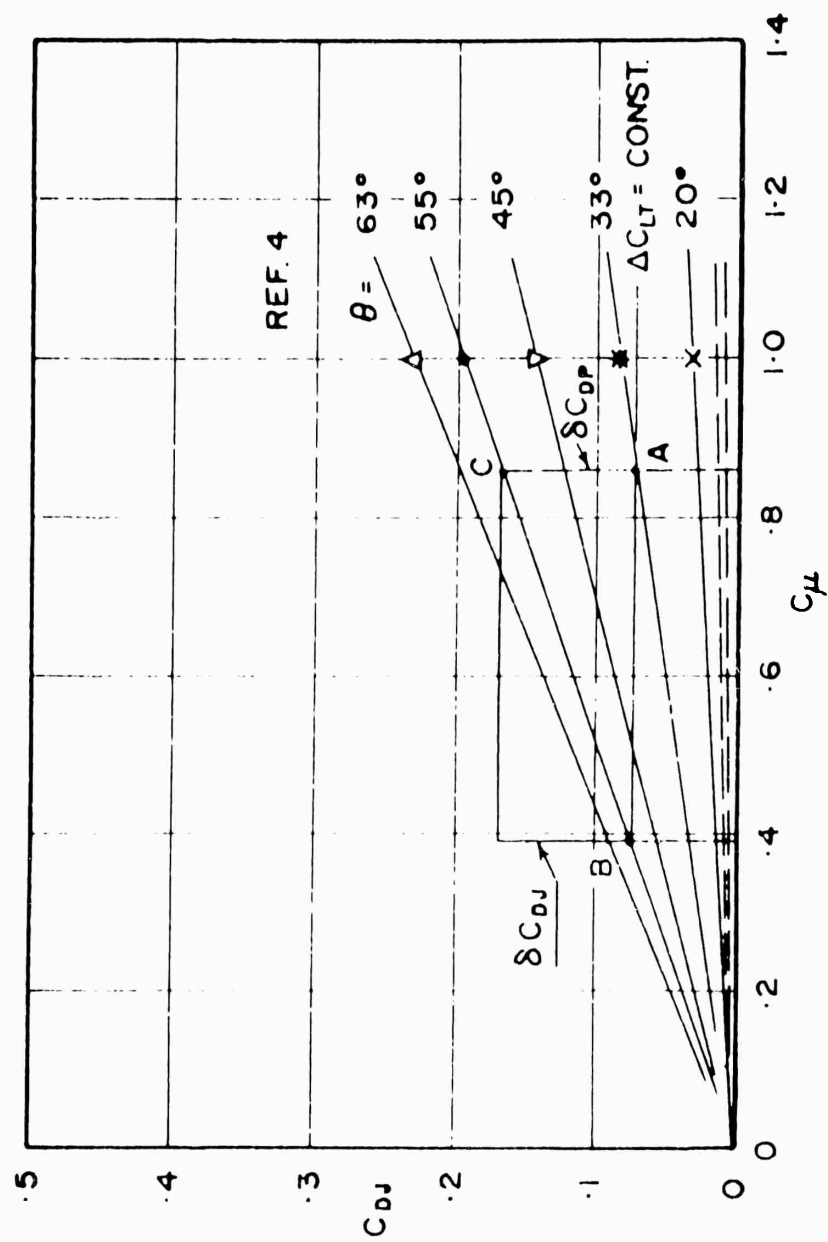


Figure 17b. The Variation of the Calculated Jet Drag (Eq. 2.26) with Jet Deflection Angle,  $\theta$  (Test Data of reference 4).

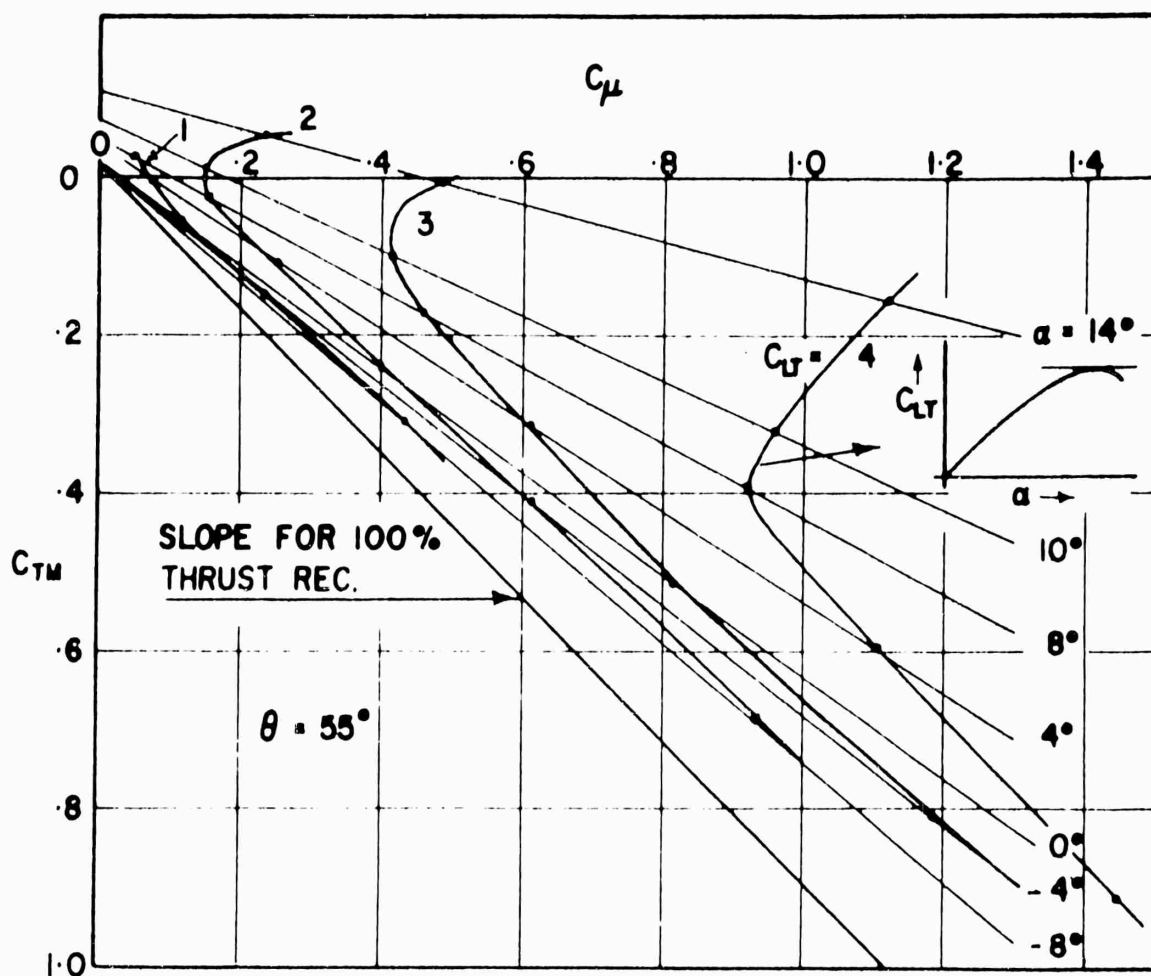


Figure 13 Thrust Recovery and Thrust and Drag Variation as a Function of Angle of Attack (Test Data of reference 4 - Pure Jet Flap).

- a) Total Thrust and Total Lift Changes Due to Blowing and  $\alpha$ .

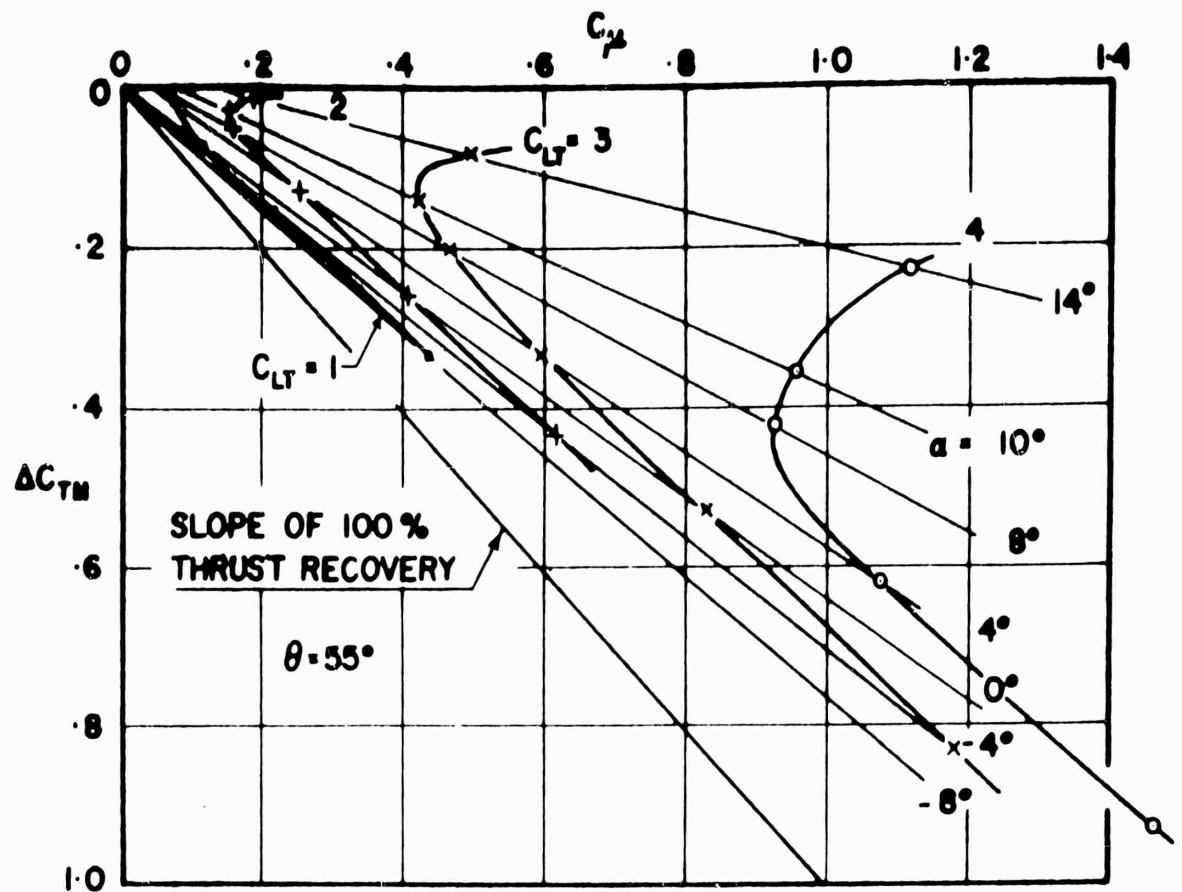


Figure 18b. Total Lift Change Due to Blowing and  $\alpha$  ; Total Thrust Change Due to Blowing Only.

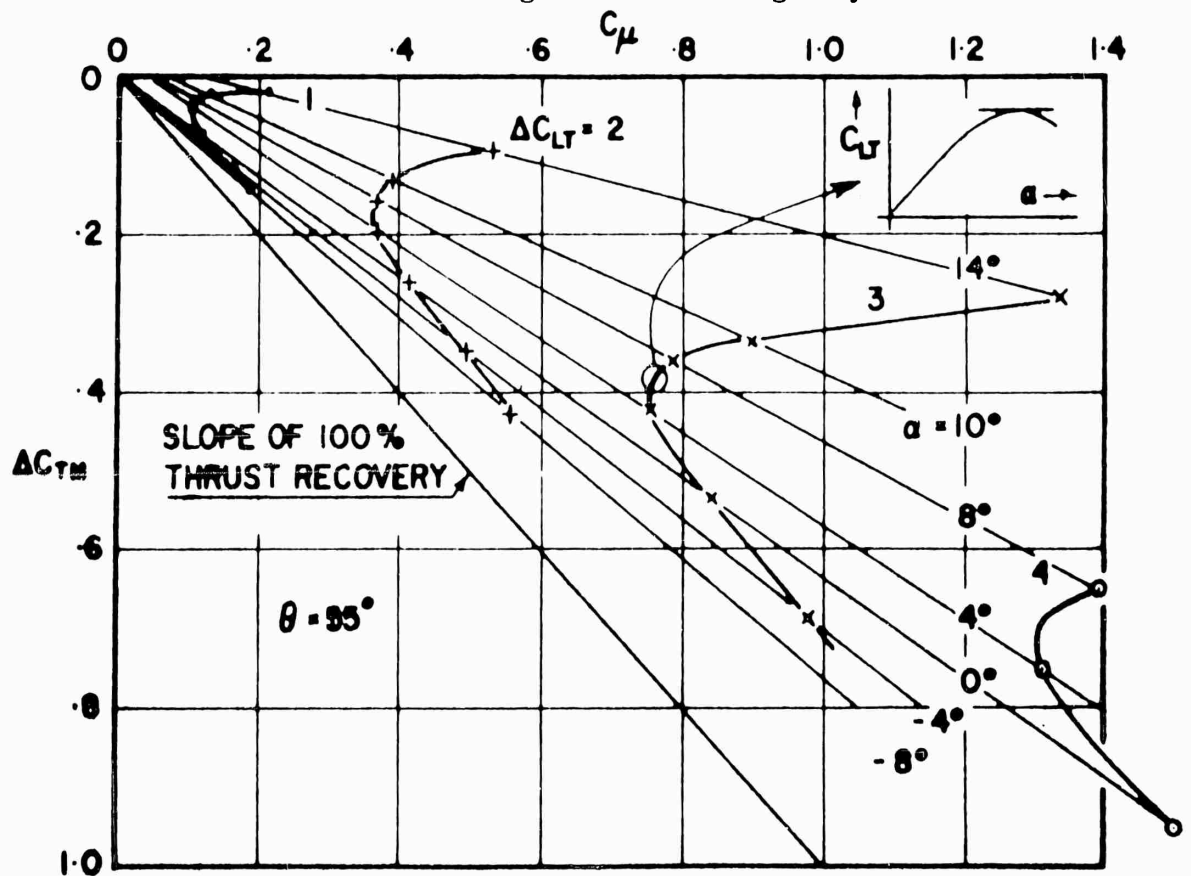


Figure 18c. Both Total Lift and Total Thrust Changes Due to Blowing Alone.

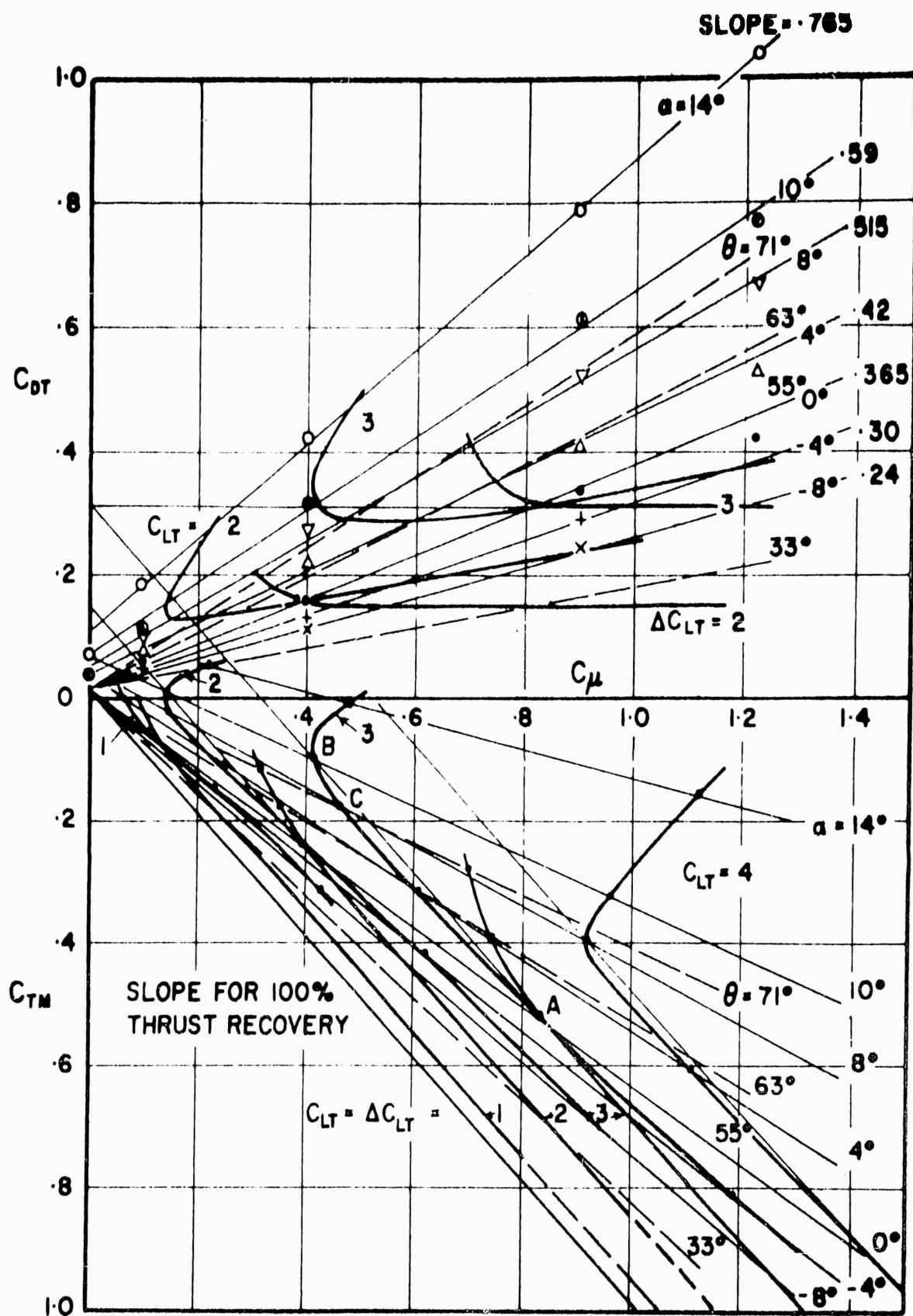


Figure 19. Jet-Flap "Characteristics" for a AR = 20 Jet-Flapped Wing at a Fixed Jet-Deflection Angle ( $\theta = 55^\circ$ ) and Changing Angle of Attack ( $\alpha$ ).

- a) Thrust Recovery and Thrust and Drag Variation at Constant Lift (Test Data of reference 4).

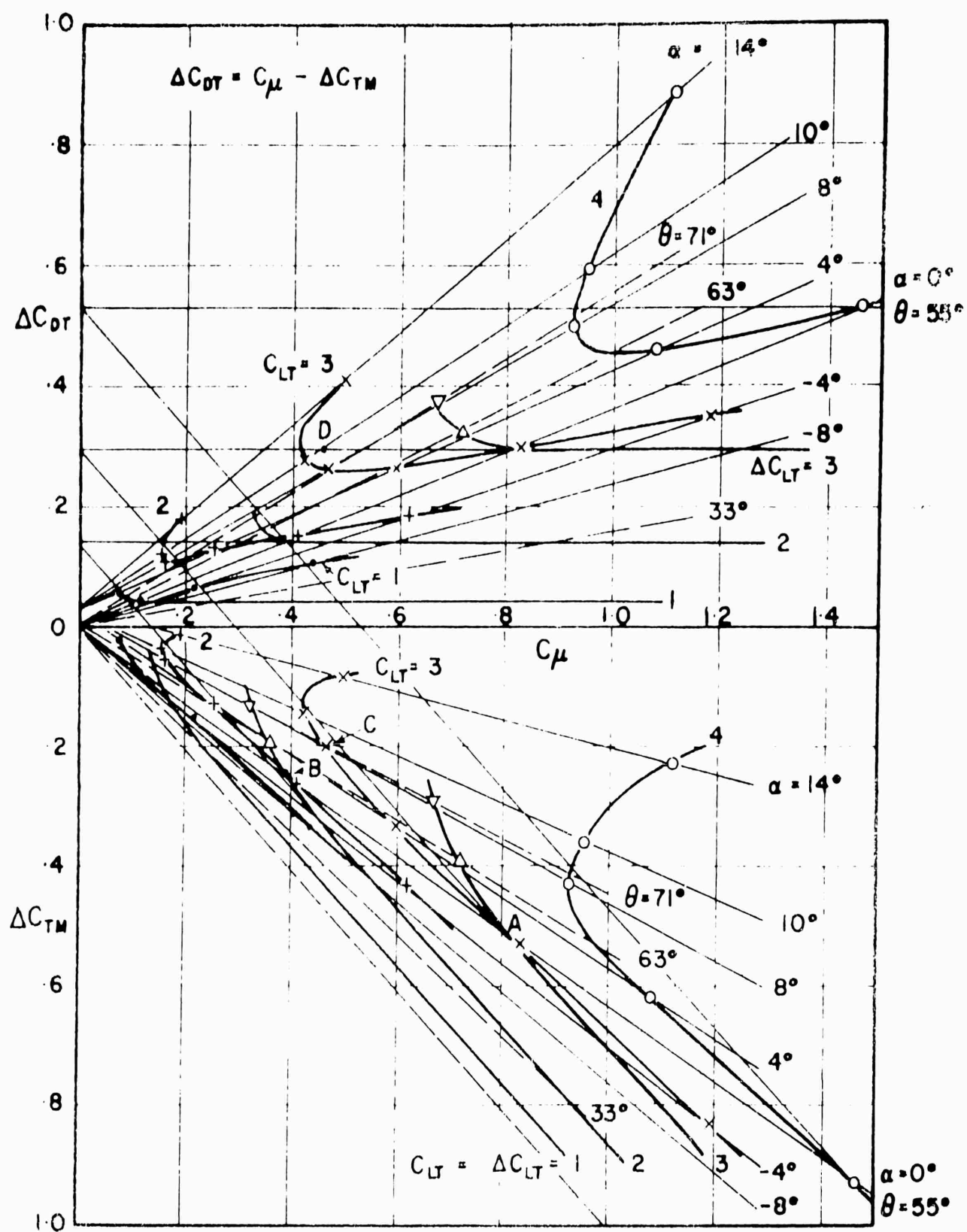


Figure 19b. Thrust Recovery and Thrust and Drag Variation Due to Blowing at Constant Lift (Test Data of reference 4).

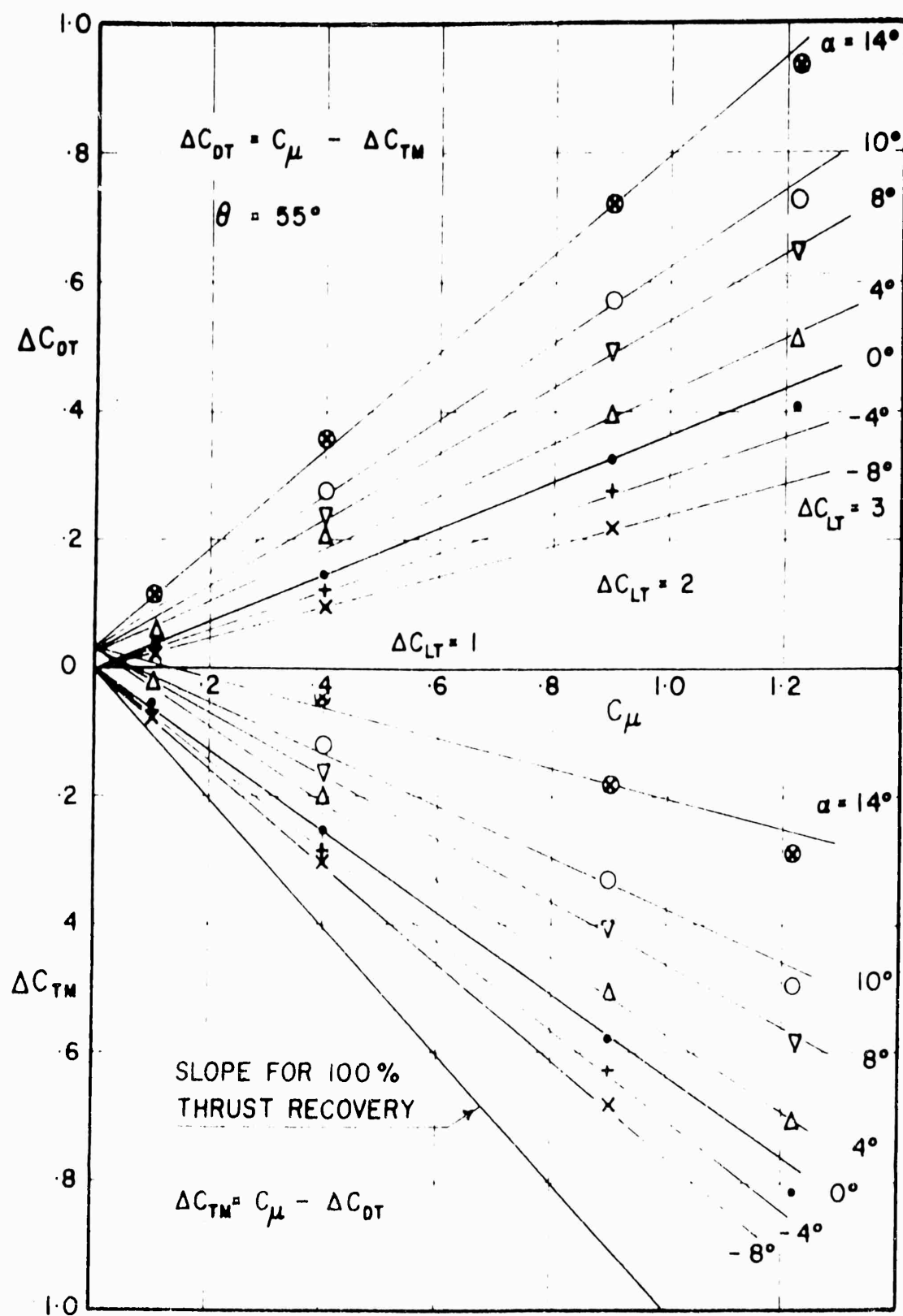


Figure 20. The Variation of the Drag and Thrust of a Pure Jet-Flapped Wing with Blowing and Angle of Attack (Test Data of reference 4).

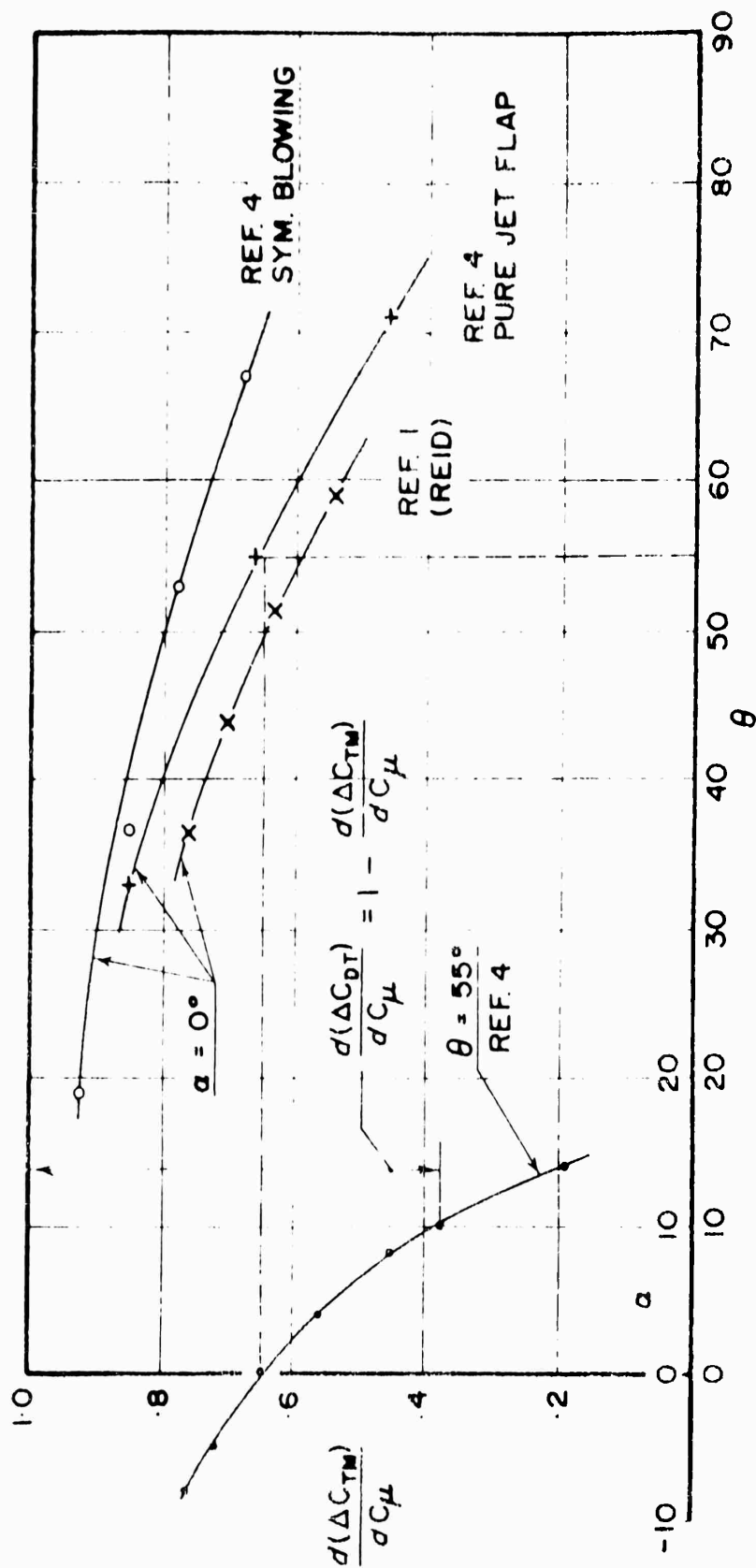


Figure 21. The Effect of Jet-Deflection Angle and Angle of Attack on the Rate of Change of Thrust and Drag.

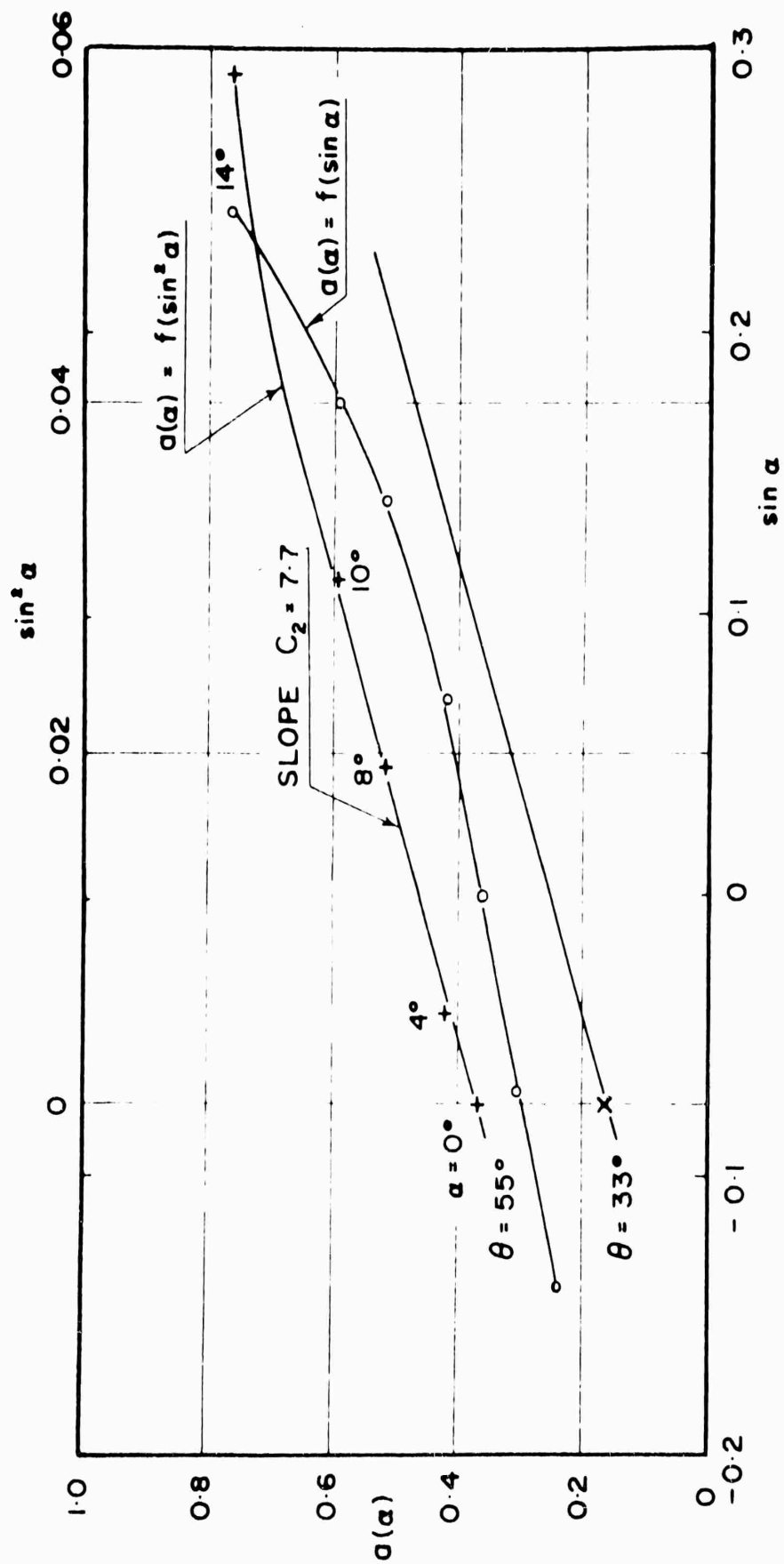


Figure 22. The Slope  $d a(\alpha) / d \sin^2 \alpha = C_2$  for the Pure Jet-Flapped Wing of reference 4 at  $\theta = 55^\circ$ .

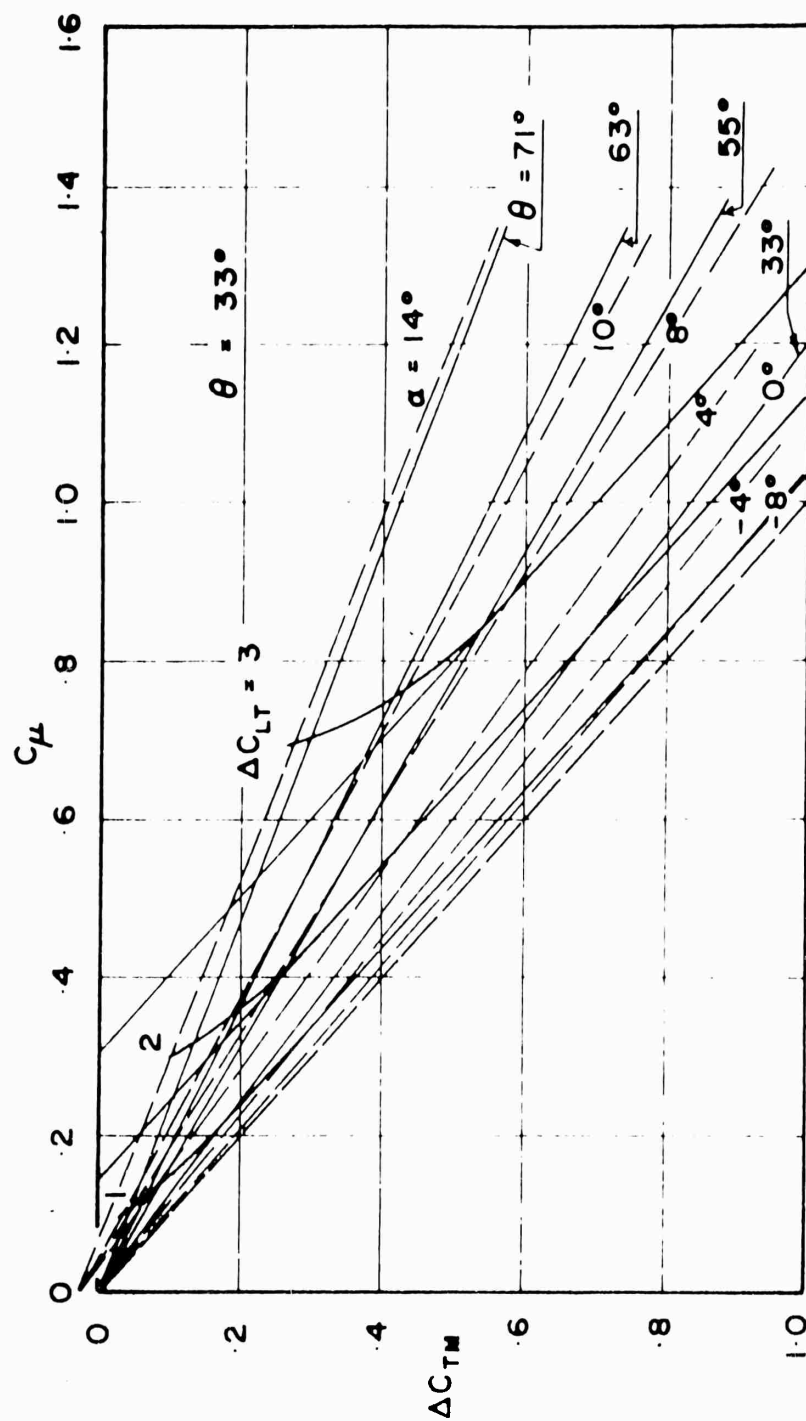


Figure 23. A "Constructed Characteristics" for the Pure Jet Flapped Wing of reference 4 at  $\theta = 33^\circ$ .

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clusively as it has been proven theoretically. Next, a "characteristics" of a jet-flapped wing is presented, which, for a preselected lift furnishes any number of combinations of rate of blowing, jet-deflection angle, and angle of attack. Simultaneously, the performance and the economy of lift production can be evaluated from the associated thrust and drag values. By optimizing the lift production with respect to the lowest expenditure of blowing at the smallest possible drag, an "operating line" for the most economical operation of a jet-flapped wing can be added to the "characteristics". Logically, the range of most economical jet-flap operation coincides with the range over which the measured thrust indicates complete thrust recovery. It is shown that this portion of a "characteristics" can be artificially set up.clusively as it has been proven theoretically. Next, a "characteristics" of a jet-flapped wing is presented, which, for a preselected lift furnishes any number of combinations of rate of blowing, jet-deflection angle, and angle of attack. Simultaneously, the performance and the economy of lift production can be evaluated from the associated thrust and drag values. By optimizing the lift production with respect to the lowest expenditure of blowing at the smallest possible drag, an "operating line" for the most economical operation of a jet-flapped wing can be added to the "characteristics". Logically, the range of most economical jet-flap operation coincides with the range over which the measured thrust indicates complete thrust recovery. It is shown that this portion of a "characteristics" can be artificially set up.

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